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PROJECT APOLLO

AN ANALYSIS OF GUIDANCE MONITORING AND FAILED SYSTEM DETECTION AND IDENTIFICATION FOR THE LM POWERED DESCENT MANEUVER

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INTRODUCTION

The LM powered descent to the lunar surface is controlled automatically by the primary guidance system throughout most of the landing maneuver. During this time, the crew is required to monitor the on-board guidance systems. The primary objectives of the monitoring process are to (1) assure that the PNGCS is operating satisfactorily so the mission can be continued, (2) provide the crew with the means for detecting a failed or degrading guidance system, and (3) provide a method for identifying the failed guidance system.

A number of studies have been conducted to analyze guidance system monitoring problems (references 1, 2, & 3). The references examined the effect of guidance component failures on the descent trajectory, related these to the ability of the crew to detect and identify guidance system failures before a safe abort was no longer possible, and then devised schemes to monitor the on-board guidance based on the study results. In addition to the analytical studies, two piloted simulation studies have been conducted at contractor facilities to test the feasibility of two monitoring concepts.

These analytical studies and piloted simulations demonstrated that on-board monitoring of the LM guidance systems was feasible. Since the time the studies were completed, however, the guidance equations have been better defined and the operational characteristics of the guidance components obtained from test articles. For these reasons, the Guidance and Control Division has reassessed the guidance monitoring concept using the updated information and has evolved a scheme for performing the on-board monitoring technique. The present report discusses the descent trajectory characteristics, the on-board guidance systems, the crew-display interface, identifies critical guidance failures and their influence on crew safety and mission success, the probability of detecting the failures, and discusses a monitoring concept that appears to satisfy the monitoring requirements for the LM powered descent maneuver.

DESCRIPTION OF POWERED DESCENT TRAJECTORY

The powered descent trajectory (figure 1) begins at a pericynthion altitude of 50,000 (above the reference sphere) with the LM pitched back some 112° with respect to the landing site. Range to the landing site is of the order of 250 n.mi. and the total inertial velocity somewhat more than 5500 ft/sec. The trajectory is characterized by a gradual increase in descent velocity from 0 at pericynthion to -135 ft/sec at an altitude of about 35,000 feet. From there it decreases sharply to about -10 ft/sec and increases rapidly to its maximum value of the order of -160 ft/sec near higate. The downrange velocity decreases rather steadily at an almost constant rate, from 5564 ft/sec at pericynthion to about 600 ft/sec at the higate transition point. Two target changes occur, one where the guidance shifts from the false target to the higate target (approximately 200 seconds into the descent), the other at higate where the shift is to the low gate target. In addition, the descent engine is throttled down from the 92.5% level to about 50% some 370 seconds after descent engine ignition. Following the pitch at higate, both the forward and vertical velocity decrease almost linearly until the hover point is reached.

DESCRIPTION OF GUIDANCE AND NAVIGATION SYSTEMS

The LM has two on-board systems (1) the primary navigation and guidance system (PNGCS) and (2) the abort guidance system (AGS). In addition to these two systems, it is anticipated the manned spaceflight network (MSFN) will be able to provide navigation information during the powered phase. While the landing radar (LR) and rendezvous radar (RR) are normally considered to be a part of the PNGCS, the RR has no LGC interface with the PNGCS during powered descent and the LR data are not used by the PNGCS until an altitude of the order of 24,000 feet is reached (about 250 seconds after descent engine ignition). A block diagram of the guidance systems is shown in figure 2.

Primary Guidance System

The main elements of the PNGCS are the guidance computer (LGC), the inertial platform (IMU), and the input/output unit (DSKY). The LR and RR also are considered to be a part of the PNGCS, but can operate independently of the other elements of this system. The PNGCS computes the descent steering commands throughout the landing. The system is initialized from lunar orbit navigation data prior to separation and realigned before the start of powered descent. The PNGCS operates as a pure inertial system to an altitude of the order of 25,000 feet (about 250 seconds after ignition). At this altitude, the LR measurement of altitude is combined with the LGC altitude estimate (reference 4) to wash out differences between the LGC and LR altitudes. To prevent transients and to take into consideration the possibility of terrain uncertainties, the LR update is weighted, beginning with 0 at 25,000 feet and increasing linearly to about 0.55 at an altitude of 100 feet. The LR update of LGC velocities is presently programmed to begin shortly before higate, again with a weighting of zero at an inertial velocity of 1650 ft/sec increasing linearly to 0.4 (vertical) and 0.7 (lateral, forward) at the hover point.

Abort Guidance System

The principal elements of the abort guidance system are the inertial sensor (ASA), the Computer (AEA), the input/output unit (DEDA), and the autopilot section (CES). The AGS is initialized by the PNGCS prior to separation and aligned to the IMU before the descent burn. The AGS provides abort capability following a PNGCS failure, but does not compute steering commands for the descent landing maneuver. However, it does maintain an independent up-to-date knowledge of the descent trajectory which can be displayed either through the flight instruments or DEDA.

Manned Spaceflight Network

The anticipated performance of the MSFN is discussed in reférence 5. This reference indicates the determination of the LM state vector during powered descent will be relatively inaccurate but that the measurement of earth-LM relative range rate is expected to be of the order of 1.5 ft/sec, 3 sigma. The MSFN range rate data are subjected to coordinate transformation and smoothing. In addition to this, the MSFN has access to the on-board guidance systems (plus the RR and LR data) through the LGC and normal downlink telemetry channels. Previous analysis (reference 3) has shown the inherent communication time delay to be of little consequence for the monitoring process.

CREW-GUIDANCE INTERFACE

The crew can monitor the guidance systems and radars using the DSKY, DEDA, and flight instrument groups. Figure 3 shows the flight instruments available to the left and right hand crew members and 4 the DSKY and DEDA. While both crew members can read the DSKY, normally only the right hand crewman will read the DEDA because of the difficulty the left hand crewman has in reading this instrument. Also, both radars must be operated by the command pilot. A description of the flight instruments is contained in the appendix.

GUIDANCE FAILURE MODES

The on-board guidance systems have been designed to have both accuracy and high reliability and are expected to function normally throughout the descent and to operate within their design limits. Both systems are, however, subject to a number of failures that can either cause a complete disruption of the output or so seriously degrade their performance they should no longer be used to control the spacecraft. Many of the failures the guidance systems are detected automatically, either in the guidance systems themselves or by other subsystems. Failures of this type will be detected by the crew rapidly as they will be informed of these through the caution and warning devices. Among failures that will be detected in this manner are the guidance computers, power supplies, RCS jets, engine trim gimbals, parts of the inertial subsystems, etc. Failures of this type are of concern to the overall spacecraft status, but do not necessarily influence guidance monitoring.

Failure Types

In general, the failures that are of concern in guidance monitoring can be grouped in one of two broad categories: (1) "hard-over" and (2) slowly degrading. The first class of failures tend to be classed with the automatically detected failures in that these failures generally result in highly abnormal spacecraft performance and will be noticed by the crew shortly after they occur. Such failures imperil the crew only if the crew fail to recognize them and take the necessary corrective action. The second category of failures are of more concern to the crew because they in fact do not cause rapid changes in either the normally expected spacecraft performance or the trajectory. While this type of failure creates no immediate danger to the crew, allowing them to persist over long periods of time can lead to unsafe flight conditions in some cases. However, it is precisely the fact that they must exist for extensive periods of time before they cause trouble that allows the crew time to detect them, assess their effect, and take corrective action.

NAVIGATION UNCERTAINTIES

The navigation uncertainties associated with the descent trajectory arise from the initialization errors and the deviations resulting from inaccuracies of the guidance system inertial components. A detailed analysis of the PNGCS and AGS including the initialization uncertainties has been conducted by the Guidance and Control Division and reported in reference 6. The 1 sigma uncertainties associated with the PNGCS and AGS are given in the reference for (1) the estimated LM inertial state vector, (2) the estimated LM altitude and altitude rate, and (3) the estimated LM-CSM relative range and range rate. In addition to these data, the error source partial derivatives for the thrusting phase were determined at specific intervals of time along the trajectory and, for use in this analysis, transformed to an instantaneous local vertical coordinate system. These data represent the expected deviations in the PNGCS and AGS during normal operation.

The results of the analysis of reference 6 have been plotted in figure 5, which shows the total uncertainty (initialization and guidance) and the uncertainties resulting from the hardware for the PNGCS and the AGS. The uncertainties associated with the hardware components of the PNGCS and AGS positions and velocities are shown in figures 6 and 7, respectively. Finally, the expected LM-CSM relative range rate uncertainties for the two systems are plotted in figure 8.

Initialization and Guidance Hardware Uncertainties

The effect of the initialization errors and guidance hardware uncertainties on the trajectory components is essentially the same for both guidance systems. The largest total uncertainty is in the downrange component and, as can be seen in figures 5a and 5c, is almost entirely caused by the initial position uncertainty. The uncertainty in crossrange and altitude positions begins with the entire uncertainty caused by the initialization errors with the hardware errors gradually becoming predominant. The downrange and crossrange velocity uncertainties are initially caused by the initialization errors but these are rapidly submerged by the guidance hardware effects. The most sensitive trajectory components in both position and velocity are altitude and crossrange with the most insensitive trajectory components to hardware errors being the downrange component. This would be expected as the descent engine is thrusting at the maximum value during most of the time shown on figure 5. Except for engine thrust uncertainties (which may swamp the effects of predicted hardware performance), only hardware deviations affecting pitch or yaw attitude will cause errors in velocity and position. The magnitude of the downrange velocity error is proportional to time, spacecraft deceleration, and 1 minus the cosine of the pitch or yaw attitude error. Therefore, except for very large attitude errors, the downrange error caused by hardware will be of little consequence. These same pitch and yaw attitude errors, however, influence altitude and crossrange proportional to time, spacecraft deceleration, and the sine of the attitude errors. The end effect for altitude and crossrange is that the error in acceleration from the attitude errors can be significant compared to the nominal acceleration along these two axes. Therefore, the downrange (or total) velocity can be used to measure engine performance while altitude rate and lateral velocity can be used to detect off-nominal guidance performance.

Principal Hardware Error Sources

The principal hardware error sources for the PNGCS and AGS are shown in figures 6 and 7, respectively. The figures show the total uncertainties in position and velocity plus the hardware error sources affecting that particular trajectory component. For the PNGCS, the primary source of error arises from initial misalignment. In fact, figure 6 shows that misalignment in the Y and Z (report LM lateral and vertical) axes has from 3 to 10 times more effect on the expected uncertainty than any of the other hardware errors. The sources considered and their effect on the trajectory are shown in table 1. The significant item of interest is that errors either affect in-plane or out-of-plane velocities, but not both simultaneously. Figure 7 shows that the principal AGS hardware error sources are accelerometer non-linearity, Y- and Z-axis constant gyro drift, and Y- and Z-axis initial misalignment. In general, the remaining AGS hardware sources have secondary effects compared to the primary sources. The pattern of hardware effects noted in table 1 for the PNGCS is also true for the AGS.

Effect of Guidance System Degradation on Descent Trajectory

The principal effect of larger than nominal IMU errors on the guidance systems is to cause the PNGCS to guide to an off-nominal trajectory. To determine this effect on crew safety, the 1 sigma altitude and altitude rate data of figures 6 and 7 were added linearly to the nominal trajectory shown in figure 1 and extrapolated until the deadman's curve* was penetrated. The number of PNGCS 1 sigma deviations in altitude and altitude rate required for penetration of the curve (which represents the limit of descent engine abort capability and therefore an absolute limit for crew safety)were established and have been plotted in figure 9. This curve represents the magnitude of the trajectory deviations in altitude and altitude rate that must be detected to assure safe aborts with the descent engine in the event of no LR altitude update. Figure 9 shows that the guidance system must be extremely degraded to cause penetration of the no abort region even after 450 seconds of descent burn, the approximate time of higate.

Magnitude of Component Deviations Necessary for Penetrating No-Abort Region

The magnitude of the PNGCS component errors to cause penetration of the deadman's curve, in terms of their normal 1 sigma performance, can be determined assuming the errors are statistically independent; i.e., the total hardware error is the root-sum-square of the individual component contribution. Thus, if K_δ is the number of normal 1 sigma deviations required for penetration, K_V the normal 1 sigma trajectory deviation at t, and K_J the component contribution at t, then

$$K(t) = \left[1 + K_V{}^2\ (t)\ (K_\delta^2 - 1)/K_J{}^2(t)\right]^{\frac{1}{2}} \qquad (4)$$

where K(t) represents the number of 1 sigma deviations of the error source to cause penetration (reference 3). The curves of figures 6 and 7 can be used to establish numerical values for the various components.

*Defined herein as consisting of biases of 1500 feet for R+A and 800 feet for local slope uncertainty plus a 3 sigma allowance of 2300 feet for terrain uncertainty. The biases are added to the descent engine deadman's curve and the terrain uncertainty root-sum-squared with the PNGCS altitude dispersion.

Effect of PNGCS Errors - Figure 10 shows the magnitude of PNGCS component deviations required to cause penetration of the deadman's curve as a function of time into the descent burn. This figure shows that even as late as 300 seconds into the burn the component deviations, in terms of their normal 1 sigma operation, must operate between 30 and 500 times off-nominal before the no-abort region is penetrated. These numbers are, of course, meaningless in the statistical sense and are indicative of components that can no longer serve any guidance function. The effects of such failures will be obvious to the crew well before any adverse safety of flight condition is approached.

DETECTION OF DEGRADED AND FAILED GUIDANCE SYSTEMS

At least two techniques can be used for guidance monitoring and failed system detection. One technique utilizes the comparison of selected PNGCS and AGS trajectory variables against nominal expected descent trajectory variables. The second technique employs the principle of comparing the difference between PNGCS and AGS trajectory variables to their nominally expected time-wise deviations. The analysis of reference 3 leads to the conclusion that while either technique satisfied the detection criteria*, the reference trajectory technique was more in line with normal piloting procedures. In particular, the scheme inherently gave a "how-goes-it" trajectory assessment and at the same time gave an early indication of a degraded system without reference to additional charts.

Primary Trajectory Variables for the Detection of Guidance System Performance

In the reference trajectory monitoring scheme, the crew periodically examines selected variables to determine whether they remain within their expected bounds, normally the ± 3 sigma deviations as operation outside these limits is considered to represent unsatisfactory guidance performance. From a guidance monitoring viewpoint, the variables of primary interest are the velocities associated with downrange, crossrange, and altitude trajectory components. As long as these variables (in particular the crossrange and altitude velocities) remain within their 3 sigma deviations about the nominal, a safe descent to higate occurs if the pericynthion conditions are correct. However, because of the importance of altitude in the later stages of flight, this variable should be monitored to achieve continuity in the monitoring process.

The basic conclusions of reference 3 are substantiated by the data of figure 5 and the nominal trajectory and deadman's curve shown in figure 1. If the uncertainties of figure 5 are multiplied by 3 and added to the appropriate variables of figure 2, it is seen that the

*Both techniques employ the principle of differencing although by different means.

crew will not encounter a safety of flight condition until after higate has been passed, even without a LR update of altitude. In fact, the discussion relative to the deadman's curve and the graph of figure 9 show that without LR data the altitude and altitude rate must deviate 6 times the nominal 1 sigma dispersion before the deadman's curve is penetrated at higate. The primary question of concern is what magnitude of failures or degradations the crew can be expected to detect using the reference trajectory monitoring technique.

Theory of Failed Guidance Detection

A check on guidance operation is possible by comparing the expected upper and lower 3 sigma bounds about the reference trajectory variables. The effect of inertial component degradation failures on a trajectory variable will be such that the normal ± 3 sigma bound of the variable will be exceeded sometime in the descent. The total deviation of any trajectory variable about its nominal value is

$$K_V{}^2 = \sum_{i=1}^{n} K_i{}^2 \qquad (1)$$

where K_V is the normal 1 sigma deviation of a variable and K_i the individual error source contribution to the total deviation. Consider the j -th source and the effect of it failing on the trajectory. Mathematically,

$$K_V = \sum_{i=1}^{n} K_i, \; i \neq j + K_j \qquad (2)$$

Because K_j has failed, it has no statistical properties and therefore acts simply as an increasing bias on the nominal value of the variable. If only K_j is considered, it will at some time force the normal 3 sigma bound about the reference value of the variable to be exceeded. Therefore, the crew by monitoring the ± 3 sigma bounds would have an indication of a failure by time t_1 (figure 11). However, the statistical properties of the remaining error sources cause a Gausian distribution about the off-nominal value. Because of this distribution, the actual value observed by the crew is equally likely to be above or below the mean of the error source and thus there is a 50% chance the crew will detect the existence of the degraded guidance system by time t_1. If the variable is allowed to deviate further, the chance of detection increases accordingly. At t_2 in figure 11, the variable has deviated to the point where the nominal ± 3 sigma boundary and the -3 sigma distribution about the mean of the error source coincide. The crew at this time has a 99.86% chance of detecting that the guidance system has degraded (reference 1). The numerical value for the magnitude of the variable required to assure a 99.86% probability of detection any time t can be calculated from the relationship:

$$m(t) = 3K_v(t) + 3\left[K_v^2(t) - K_j^2(t)\right]^{\frac{1}{2}} \qquad (3)$$

In terms of the nominal 1 sigma contribution of K_j to K_v, the number of 1 sigma deviations K_D necessary to attain the 99.86% chance of detection is

$$K_D(t) = m(t)/K_j(t) \qquad (4)$$

Magnitude of Component Failures Required for
99.86% of Probability of Detecting a Failed Guidance System

The value of m(t) obtained from equation (3) represents the magnitude of the deviations of a variable from the nominal required to assure a 99.86% to be expressed in terms of the 1 sigma deviations of individual inertial components that contribute to m(t). From equation (3) it may be seen that the magnitude of m(t) is determined by the relative values of $K_V(t)$ and $K_j(t)$. For example, using the data of figure 6a (PNGCS downrange error), the value of $K_V(300) = 220$. Using the Y-axis initial misalignment as the error source, $K_j(300) = 200$ and $m(300)$ therefore is equal to 919. In terms of the normal 1 sigma uncertainty, the variable (downrange error) must deviate roughly 4.2 times the normal 1 sigma deviation (220) to obtain a 99.86% chance of detecting this particular failure. In contrast, for the Z-axis accelerometer bias, m(300) is 1320 and the variable must deviate almost 6 times the normal 1 sigma amount for the same level of detection probability. In terms of K_D (the number of 1 sigma deviations of the individual components), at 300 seconds into the descent, the Y-axis initial misalignment and Z-axis accelerometer bias must be 4.2 and 82.5 times their respective normal 1 sigma deviations before the crew has a 99.86% chance of detecting something is wrong with the PNGCS.

To illustrate the magnitude of component degradation required for detection, equations (3) and (4) have been used to determine K_D for the components affecting altitude rate and lateral velocity as computed by the PNGCS and AGS. The results have been plotted in figures 12-14, inclusive. From figure 11 it is seen that the most likely degradation that will be detected by monitoring altitude rate is Y-axis misalignment, which has a detection level of about 4 times the normal 1 sigma deviation. The remaining error sources have detection levels of between 40 and 60 times their respective 1 sigma values. The monitoring of PNGCS lateral velocity results in the detection of component degradations as indicated in figure 13. Monitoring of the AGS altitude rate and lateral velocity provides the detection levels shown in figures 14 and 15, respectively.

IDENTIFICATION OF DEGRADED OR FAILED GUIDANCE SYSTEMS

The LM is controlled automatically by the PNGCS steering commands throughout the major portion of the powered descent. In controlling the LM, the PNGCS acts as a purely inertial system until the time the LGC state vector is updated by the LR. Because the steering commands are derived from the inertial system, the descent until the start of update is unique and repeatable and entirely predictable within the uncertainties of the inertial components and and DE. Thus, once the guidance constants have been established, the trajectory through inertial space is the same regardless of where the landing site is located. The trajectory computed by the AGS is also predictable as it too is referenced to inertial space. Update of the LGC by the LR begins at an altitude of the order of 25,000 feet, which corresponds to a nominal descent time of the order of 260 seconds. However, the weighting factor at this time is zero (weighting of LR altitude into the LGC is defined as $W = 0.55(1 - h/25{,}000)$) and, unless there are extremely large altitude differences between the LGC and LR, the LR data do not begin to really influence the trajectory until perhaps 300-350 seconds into the descent. Thus, half or more than half of the powered descent trajectory can be predicted within the uncertainties associated with the LM systems affecting guidance operation.

Use of Nominal Reference Trajectory

Assurance that the two on-board guidance systems are operating satisfactorily can be accomplished during at least half of the descent by comparing the PNGCS and AGS trajectory performance against the nominally expected trajectory. If upper and lower bounds based on expected component performance are established about the nominal trajectory variables, the crew knows the systems are operating correctly as long as these bounds are not exceeded. A degraded or failed guidance system is detected by noting whether the systems operate outside these bounds. The procedure breaks down, of course, whenever the update of the LGC state vector by the LR begins to force the guidance system to conform to actual terrain variations. However, by this time in the descent the crew has committed the landing approach to the hybrid system and except for periodic checks on the AGS, the monitoring process centers about the PNGCS and LR.

Failed System Identity

The identity of the failed system can be determined by conducting a guidance check using the on-board radars or the MSFN data providing the failure affects the in-plane velocity. In particular, the RR can be used for this purpose during the first 150 seconds after ignition, the MSFN until the LR acquires altitude, and the LR altitude measurement from that time until the PNGCS and LR have become essentially integrated. Lateral failures can be identified by the LR or visually after passing higate.

Use of RR - Once a failed guidance system has been detected, the RR can be used to check the identification of the faulty system if the time into the descent is less than 150 seconds (point at which the tape indicator reads minus 700 ft/sec). This is accomplished by addressing the DEDA to call up LM-CSM relative range rate as computed by the AGS. The RR measured range rate is read from the tape indicator and compared with the AGS range rate. If the two readings agree (within some normal limit) the PNGCS is the failed system; if the readings disagree, the AGS has failed. Because the comparison is between the AGS and RR, the uncertainties associated with the two systems as well as data readout resolution must be considered in determining what level of deviation the RR can verify. The 1 sigma uncertainties associated with the AGS are shown in figure 8(b). Readout on the DEDA is to 1 ft/sec and resolution of the RR output on the tape indicator under the prevailing conditions is of the order of 2 ft/sec. Combining these shows that the difference between the RR and AGS readings must be roughly 5 ft/sec at 59 seconds and 9 ft/sec at 160 seconds for the crew to be sure that the failed system has been identified. Using this information and the data of figure 8, the minimum trajectory deviations for identifying a failed guidance system using the RR have been plotted in figure 16. At 50 seconds into the descent, the crew can identify a PNGCS trajectory deviation of 25 sigma and a 10 sigma AGS trajectory deviation. An AGS deviation of 6 sigma can be correctly identified at 100 seconds, which is the limit for detecting a failed guidance system. The PNGCS trajectory must deviate about 15 sigma at 100 seconds and approximately 10 sigma at 150 seconds before positive identification is possible. Note on the curve that penetration of the no-abort region is of no consequence this early in the descent so that the crew is not time constrained (except for the tape meter limit being exceeded before verification is completed) with respect to safety of flight.

Use of MSFN - Analyses to date have indicated the LM-earth relative range rate as measured by the tracking stations will be excellent (reference 4). The LM-earth range rate must be transformed to equivalent LM trajectory variables or the PNGCS-AGS data on the downlink transformed to range rate. In either case, this must be performed on the ground in real time, the data compared, and voice transmitted to the LM crew when necessary. However, once a failed system has been detected (which can also be done by MSFN), identification of the faulty system in this period is not time critical with respect to crew safety. Thus, the confidence that can be placed on MSFN for assisting the crew in identifying the failed system depends primarily on how accurately the onboard guidance data can be converted and compared. If the accuracy is no worse than twice the 3 sigma accuracy specified in reference 4, MSFN should be able to identify the failed system very shortly following the knowledge that one of the two onboard systems has failed. The trajectory deviation necessary to positively identify should be of the order of 8-10 times the normal 1 sigma deviation.

Use of LR - LR altitude data are expected to be available between 25,000 and 30,000 feet although there is a possibility lock-on will occur slightly before this. Timewise, LR altitude should become available around 200-260 seconds after the start of the descent burn. To identify, the LR altitude data can be compared against either the PNGCS or AGS altitude estimations. Data readout of the tape should be good to the nearest 500 feet and on the DSKY and DEDA to 1 foot. Accuracy of the LR if it is within the specification should be good (ref. 7) and the primary uncertainties in altitude arise from navigation errors and the lack of knowledge regarding the mean terrain altitude relative to the landing site. However, an indication of the usefulness of the LR in this role can be obtained by assuming a terrain uncertainty and combining this with the other source errors. The results of such an analysis are contained in figure 16 which shows the capability of the LR in identifying a failed guidance system. The terrain bias assumed was 3000 feet, 3 sigma. As shown, the spec LR can be expected to identify a PNGCS having a trajectory deviation of 17 times the normal 1 sigma deviation some 200 seconds into the descent. At 250 seconds, the LR will identify a PNGCS having an 11 sigma deviation or an AGS having a 7 sigma deviation. It can be concluded that any PNGCS degradation or failure affecting crew safety can be identified by the LR well before the crew is in jeopardy.

Lateral Failure Cases - For lateral failure cases, the crew can afford to wait as late as higate before identification of the faulty system is necessary. Not counting the CSM rescue capability or the fact the LM has a total velocity of near 600 ft/sec at higate, conservative limits for crew safety are of the order of 200 ft/sec and 50,000 feet out-of-plane. These limits correspond to nearly a 35 sigma off nominal PNGCS guidance performance. This means the crew can tolerate a highly degraded PNGCS to higate without any adverse effect on crew safety. There is, therefore, no reason why the crew must identify the faulty system immediately after it is suspected that one of the two systems has failed.

There is some possibility that the LR velocity measurement can be used for identification at an altitude of the order of 15,000 feet. Determination of the faulty system will be by direct comparison of either PNGCS or AGS lateral velocity. Actually, identification in this event can be determined by noting whether the LM rolls as velocity update begins. If it does, the PNGCS is at fault because the LR-LGC combination is reacting to correct the lateral drift; if no roll occurs, the AGS is the system at fault. Should the LR not provide usable velocity data before higate, the crew can wait until the pitchover at higate and visually determine the existence of a drift over of the order of 100 ft/sec or more. For smaller lateral velocities, the crew, once the LR data become available, can use the roll indication as noted before or compare LR velocity directly against the PNGCS or AGS velocity estimates.

There are, in fact, advantages to delaying an abort for out-of-plane failures as it is possible to effect a safe landing if the LR can reduce the lateral velocities to zero and a suitable landing site that is within fuel budget can be located (if the lateral velocity exceeds the ± 3 sigma value, the nominal landing ellipse will not be reached). If it is apparent to the crew that the lateral velocity is being driven toward the correct value, they can search for a suitable landing area and use the LPD to attain that area. Should no suitable landing site be found, then an abort can be initiated before an adverse safety condition is reached.

POWERED DESCENT MONITORING PROCEDURES

The preceding sections have discussed in detail some of the aspects associated with guidance system operation. Also, the theory of failed system detection and identification and the use of the onboard radars and the MSFN in identifying which of the two systems has failed is also discussed. This section is devoted to the discussion of a monitoring technique which satisfies the guidance and control requirements for the powered descent. The discussion includes operations during normal descent. The discussion includes operations during normal descent (no failures) and contingency operation procedures (failed guidance).

Nominal Descent Procedures

The guidance operation for the powered descent begins with the crew calling up the braking program (P63) approximately 30 minutes before PDI. This goes through all of the normal pre-thrust operations (platform align, digital autopilot load, AGS align and initialization, etc.) and displays the variables required for assuring the program is functioning. Once this has been completed, the LM is ready for descent. From this point, the crew monitors the guidance operation through the DSKY automatic displays and "on-call" displays plus the flight displays. In addition, the AGS trajectory computations are observed through the DEDA and flight displays.

A chart containing a time history of the trajectory variables should be used by the crew in monitoring the descent. This can be similar to table 2 which shows the required guidance variables, where they originate, and the display used to view the variable. The chart should have the ± 3 sigma bounds for each of the variables listed. Timewise, these time checks can be as close as 30 seconds, but for a major check; i.e., a full PNGCS-AGS comparison, once per minute appears sufficient for the onboard monitoring process. Also, the crew, in particular the pilot, must maintain status checks on many other subsystems and it would be unwise to load him with superfluous checks that are not required for safety. For this reason, the command pilot should probably check the PNGCS against the nominal once every 30 seconds and assist the pilot in conducting a major PNGCS-AGS comparison against the nominal every 60 seconds. In addition to the trajectory information being monitored, the command pilot has been given responsibility for checking the descent engine fuel status and the pilot responsibility for checking the RCS fuel status. The time line for the major comparison checks is shown in table 3 which also indicates the RR guidance checks.

A procedure similar to that outlined in table 3 should also be performed by MSFN. That is, the ground operations should monitor the trajectory as the crew does on board. The PNGCS-AGS trajectory variables should also be differenced and compared to the normal 3 sigma dispersions of the two systems. In addition, the MSFN measurement of LM-earth relative range rate should either be compared to a similar quantity calculated from the PNGCS and AGS data or the PNGCS and AGS data converted to MSFN doppler data. It would also be desirable, but not mandatory, for the LM-CSM relative range rate data from the RR to be compared to an equivalent MSFN measurement. The MSFN should verify the crew assessment of the trajectory at the nominal check points (or at closer intervals if voice communications do not become excessive; i.e., use negative reporting techniques).

For the nominal mission, once LR has become operational and the LGC update by the LR has been initiated, the reference to the nominal trajectory is of no further use. The only thing required for a safe approach to higate is that the altitude-altitude rate combination be acceptable. However, periodic checks should be made to compare the operation of the PNGCS and AGS to higate as this assures the crew that the AGS is operating. Once higate has been reached, the monitoring should be confined to the LR and PNGCS. By this time the crew has committed the landing approach to the PNGCS and normal piloting procedures as determined during training should be sufficient to complete the landing maneuver.

There are, however, three events not shown on table 3 that occur in program 63 that provide additional clues to PNGCS operation: (1) a shift from the false target to the higate target which changes TG, (2) the engine throttling that occurs around t_D = 5+ minutes, and (3) the pitchover at higate occurring at approximately t_D = 7+ minutes. The first two events are of excellent value because they give the crew a method of determining what the guidance and engine performance has been and a further check on fuel status. That is, if throttling occurs late, they have additional descent engine fuel available. This will be useful information later on in the landing. The second event also gives the crew information that higate (the third event) is impending.

Procedures Following Detection of a Failed Guidance System

Following detection of a degraded or failed guidance system, the crew will identify the faulty system using one of the three independent systems (LR, RR, MSFN) as the deciding vote, depending on the time into the descent. After higate, identification will be made using the LR or by visual cues obtained by noting ground track drift over the surface. The specific intervals of interest are (1) RR operational, (2) neither RR or LR operational, (3) LR operational but prior to LGC update, and (4) LR operational but after LGC update. The procedures the crew should follow in each of the cases are discussed below.

RR Operational - The RR is operational from PDI to about 150 seconds after PDI. If a guidance failure occurs in this interval, the crew should crosscheck the systems and the pilot should request confirmation from MSFN. The crew should then determine whether the failure affects in-plane or out-of-plane velocity. If in-plane, the command pilot should determine the RR reading of $\dot{R}$ from the tape indicator and inform the pilot of the reading. The pilot then checks the RR $\dot{R}$ against the AGS $\dot{R}$ estimate. Upon determining the identity of the failed system, the pilot should also request verification of the on-board findings from MSFN. For lateral failures, the crew should wait before trying to identify the faulty system.

Period of no RR or LR - In the interval between the loss of RR data and the acquisition of LR altitude data, the crew must rely on the MSFN to determine the identity of the failed guidance system. As before, if the failure affects in-plane velocity, the crew should request MSFN verification of the failure and the MSFN assessment as to which of the two systems has failed. Actually, if the altitude-altitude rate situation is not approaching dangerous conditions, the crew could well afford to wait for LR acquisition to confirm the MSFN evaluation. This action should not compromise the crew as any failure likely to result in dangerous altitude-altitude rate combinations should have been detected and identified during the early phases of braking. Again the crew should wait to assess lateral failures.

LR Operational - Operation of the LR allows the crew to revert to on-board determination of the failed guidance system providing the failure affects the in-plane velocity components. Procedurally, the verification will be done by comparing LR altitude with the PNGCS and AGS altitude estimates. The MSFN should verify the crew findings. Once the LR has begun the LGC update, the crew loses the last independent on-board means of identifying the failed guidance system. However, by this time, the crew has committed the landing approach to the PNGCS and higate is relatively close so that visual assessment of the trajectory can soon be made. Further, if the LGC has been successfully updated by the LR, the no-abort region will not be entered. In the event of lateral failures, the crew should wait until the LR velocity measurement becomes available or wait until higate and visually determine (or employ the LR) whether lateral velocities exist.

CONCLUDING REMARKS

The guidance monitoring procedure developed for the LM powered descent maneuver appears to satisfy the requirements stated in the introduction to this report. An analysis of failure effects and the characteristics of the descent trajectory indicates that the monitoring of the on-board guidance systems, detection of failed guidance systems, and the identification of the failed guidance system is not time critical with respect to crew safety and is amenable to successful landings. Furthermore, the monitoring, detection, and identification process is completely self-contained on-board the LM. The technique, however, should be repeated in the MSFN facilities to provide back-up to the crew assessment of the LM guidance status and progress of the descent.

The report has discussed the ability of the crew to detect and identify a degraded or failing guidance system. The analysis showed that only highly abnormal hardware performance will influence the ability of the crew to successfully abort as late as 400 seconds into the descent burn. In contrast to this, the analysis showed that the crew will be able to detect trajectory deviations in altitude and altitude rate resulting from component degradations of half the magnitude of those required to penetrate the deadman's curve at 500 seconds into the descent as early as 100 seconds after the burn is initiated. Deviations in the out-of-plane direction follow the same pattern. From this, it can be concluded the crew is afforded ample time to detect and identify a degraded or failing guidance system well before they must make the decision to abort or continue the landing. In this respect, the analysis failed to reveal any insidious failures that would not be detected before they affect crew safety.

The report also points out quite clearly that the PNGCS is capable of operating in a degraded mode without the awareness of the crew. This is also true for the AGS. The bounds for a 99.86% probability of detection are based on some variable departing a specific magnitude from a nominal value. If the variable being monitored fails to deviate this preset magnitude, the chance of the crew detecting the degradation also decreases. For example, if the Y-axis gyro drift is only 20 times the normal 1 sigma uncertainty rather than the 40 times required for a 99.86% detection probability, the probability of the crew detecting the abnormality is 50%. However, operation of the guidance system under these conditions neither influences crew safety and probably not the successful completion of the landing. The analysis simply points out that the hardware components are, in general, so accurate that they can operate well beyond their design capabilities without adversely affecting the landing mission. The fact that the crew has a low probability of detecting a guidance system operating in a slightly degraded mode is of little consequence.

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2. "Preliminary Abort Boundaries and Abort Monitoring Procedures", GAEC LMO-500-261, April 13, 1965.

3. "A Preliminary Analysis of Failure Detection and Guidance System Monitoring During the LM Powered Descent", MSC Internal Note No. 66-EG-32, June 29, 1966.

4. "LM PNGCS and Landing Radar Operations During the Powered Lunar Landing Maneuver", MIT Report E-1982, August 1966.

5. "Current Estimate of Manned Space Flight Network (MSFN) Capability for the First Apollo Lunar Mission", memo to FA/Director of Flight Operations from FM/Chief, Mission Planning and Analysis Division, 66-FM41-177, June 15, 1966.

6. "A Study of LM Navigation Systems Accuracies for Powered Descent, Ascent, and Abort", MSC Internal Note No. 67-EG-6, January 31, 1967.

7. "LM Landing Radar Performance Analysis", Memo EG26-66-77 from EG26/ Guidance Development Branch to E /Chief, Guidance and Control Div.

ACCELEROMETER BIAS
ACCELEROMETER SCALE FACTOR
NON LINEARITY
CROSS AXIS SENSITIVITY
INITIAL MISALIGNMENT
CONSTANT GYRO DRIFT
ANISOELASTICITY

a. Error Sources Considered

NAVIGATION EFFECT OF ERROR SOURCES					
ERROR SOURCE		TRAJECTORY COMPONENT AFFECTED			
		VELOCITIES			ALTITUDE
		DOWNRANGE	CROSSRANGE	ALTITUDE	
ACCELEROMETER BIAS	X	YES		YES	YES
	Y		YES		
	Z	YES		YES	YES
SCALE FACTOR	X	YES		YES	YES
	Z	YES		YES	YES
NON LINEARITY	X	YES		YES	YES
	Z	YES		YES	YES
CROSS AXIS SENSITIVITY	Y-X		YES		
	X-Z	YES		YES	YES
	Y-Z		YES		
	Z-X	YES		YES	YES
INITIAL MISALIGNMENT	X		YES		
	Y	YES		YES	YES
	Z		YES		
GYRO DRIFT	X		YES		
	Y	YES		YES	YES
	Z		YES		

b. Effect of Error Sources on Trajectory

Table 1 - Error Sources and Their Effect on Trajectory

	COMMAND PILOT							
	Total Velocity	Altitude Rate	Altitude	Lateral Velocity	Attitudes	T/W	T/Tc	DE Fuel
Display	DSKY	DSKY	DSKY	Cross Pointer	FDAI	Meter	Meter	Meter
Sys. / Time	PNGCS	PNGCS	PNGCS	PNGCS	PNGCS		PNGCS	
0 → 450								

	PILOT										
	Total Velocity	Altitude Rate		Altitude		Lateral Velocity		Attitude		RCS Fuel
Display	DEDA	Tape		Tape		Cross Pointer		FDAI		Meter
Sys / Time	AGS	PNGCS	AGS	PNGCS	AGS	PNGCS	AGS	PNGCS	AGS	
0 → 450										

Table 2 - Variables Monitored by Command Pilot and Pilot

Time (min)	Command Pilot	Pilot
Pre-PDI	1. Perform P63 prethrust requirements. 2. Set up flight displays	1. As command pilot
t_B-1	1. Check PNGCS V_T, h, $\dot{h}$, $\dot{y}$ against AGS. 2. Verify CSM RR lock. 3. Check PNGCS attitude and error needles.	1. Assist command pilot 2. Verify MSFN track
t = 0	1. Check PNGCS attitudes and error needles. 2. Monitor thrust transient and T/W variation.	1. Check PNGCS-AGS attitudes. 2. Notify MSFN of start of burn.
t=0 to t=1	Continue monitoring V_T, $\dot{h}$, h, and $\dot{y}$, TG, h on DSKY and from time to time compare PNGCS and AGS h, $\dot{h}$ on tapes.	Continue monitoring AGS-PNGCS attitudes, RCS fuel
t = 1	1. Compare PNGCS-AGS h, $\dot{h}$ on tapes and $\dot{y}$ on cross pointers. 2. Verify PNGCS V_T and AGS V_T are OK. 3. Verify DE fuel status. 4. Verify AGS $\dot{R}$ with RR.	1. Compare PNGCS-AGS operation (V_T, h, $\dot{h}$, $\dot{y}$) against nominal. 2. Verify RCS fuel status. 3. Check AGS $\dot{R}$ and readout to pilot. 4. Notify MSFN of status.
t=1t to t=2	Continue as from t=0 to t-1	Same
t = 2	1. As at t = 1.	1. As at t = 1.
t = 2.5	1. Verify AGS $\dot{R}$ with RR. 2. Perform LR self check and check for altitude acquisition.	1. Make final guidance check of AGS reading of R. 2. Notify MSFN of final check.
t = 3	1. As at t=1 except for RR. 2. LR acquisition check.	1. Same
t = 4	1. As at t = 3. 2. Make LR operational check to see if acquisition of altitude occurs.	1. As at t = 3.
t = 4.5	1. Make altitude acquisition check. If good, prepare for LGC update.	1. As at t = 3.
t = 5.6	1. As at t = 3, 4.	1. As at t = 3.
Prepare for Hi-gate.		

Table 3 - Nominal Descent Monitoring Procedures

APPENDIX

DESCRIPTION OF FLIGHT DISPLAYS

Display and Keyboard

DSKY is the input/output unit between the crew and primary computer. While some information is displayed automatically during the descent, the crew has several "on-call" displays available for use. Input is through the keyboard and the output is on three five-digit numerical registers (figure 4a).

Data Entry and Display Assembly

The DEDA is the input/output unit for the abort system. No automatic displays are available but the crew can call out, through the keyboard, a number of trajectory parameters. Readout is through the single five-digit numerical display (figure 4).

Flight Instrument Group

The primary flight instrument group (figure 3) consists of two attitude indicators (FDAI), two cross pointer indicators, an altitude/altitude rate or range/range rate tape indicator unit, a lunar thrust/weight meter, event time, and thrust/thrust command indicator.

FDAI - Both indicators can read either the PNGCS or AGS attitudes with the source being controlled by the attitude monitor switch located next to the FDAI. The attitude rates are obtained only from the AGS rate gyros (the LGC does not have an attitude rate interface with the FDAI). The error needles are driven by the controlling guidance system or can indicate RR LOS angles.

Cross-Pointers - The crosspointer indicators show (1) LOS rates from the RR, (2) forward and lateral velocity from either the PNGCS or LR, or (3) lateral velocity from the AGS. The RATE ERROR MON switch next to the FDAI switches the display from RR to LGC/LR and the MODE SELECT controls between the LGC and LR. For descent, the indicators have a ±200 ft/sec and ±20 ft/sec full scale range (LOS rates are not expected to be usable in powered flight). Readout resolution on the low scale is of the order of 9.5 ft/sec.

Alt/Alt Rate Tape - This unit displays altitude and altitude rate from the PNGCS, LR, and AGS. Switching is controlled through the MODE SELECT and ALT/RNG MONITOR switches located next to the T/W indicator. Readout of the altitude varies from about 500 feet to 5 feet and altitude rate to approximately 0.5 ft/sec. Static RR range and range rate readout resolution for the descent are roughly 0.5 n.mi. and 0.5 ft/sec, respectively.

T/W Indicator - The T/W indicator displays the X-axis acceleration as measured by its internal accelerometer. The unit is calibrated in terms of units of lunar gravity and can be read by the crew to 0.1 units (0.5 ft/sec^2).

Thrust/Thrust Command Meter - This is a dual indicator that displays engine thrust (left side) and LGC thrust command (right side). In automatic flight, the thrust command indicated will be the true LGC command less the normal manual throttle setting of 10% of full thrust. The meter output can be read by the crew to the order of 2½%.

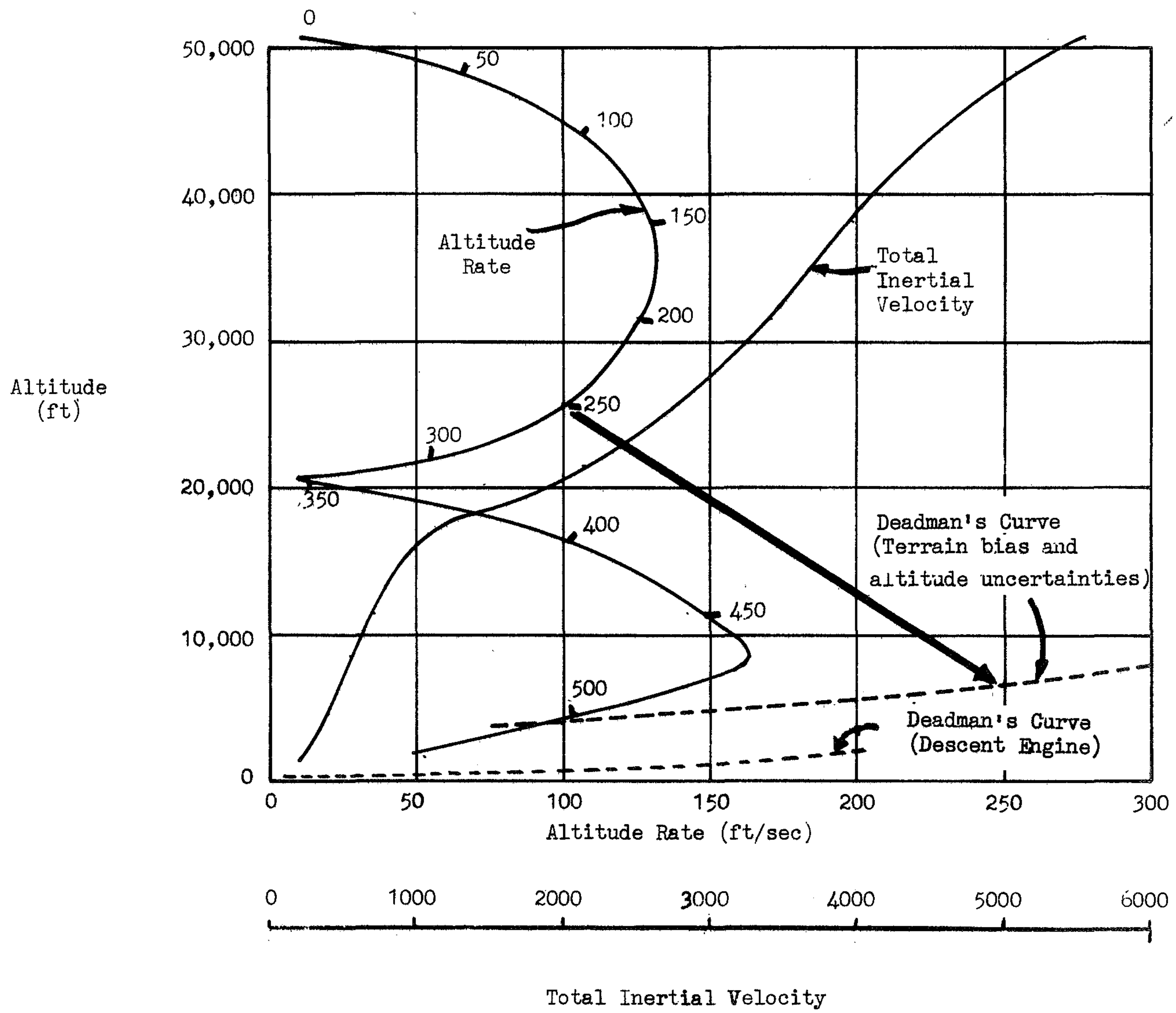


Figure 1 - Nominal Descent Trajectory

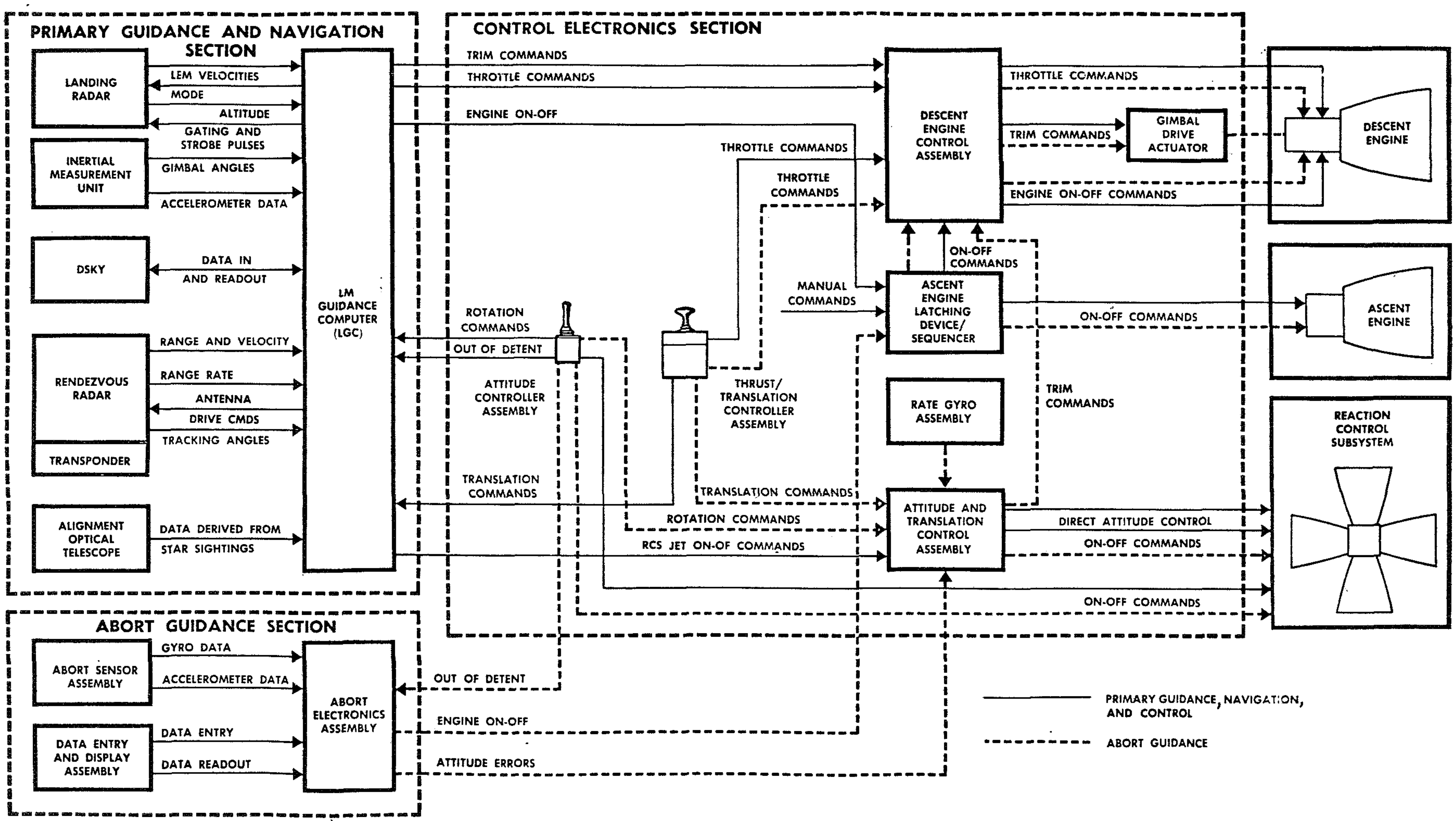
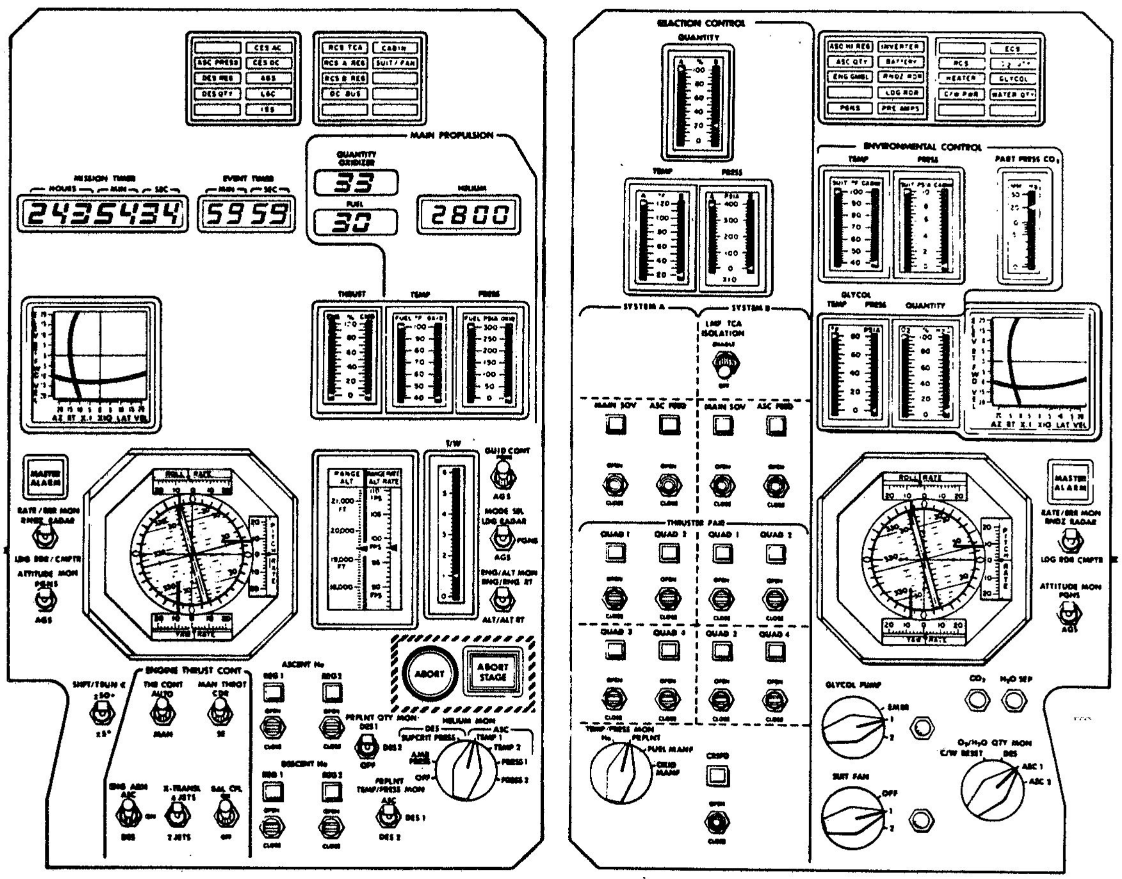
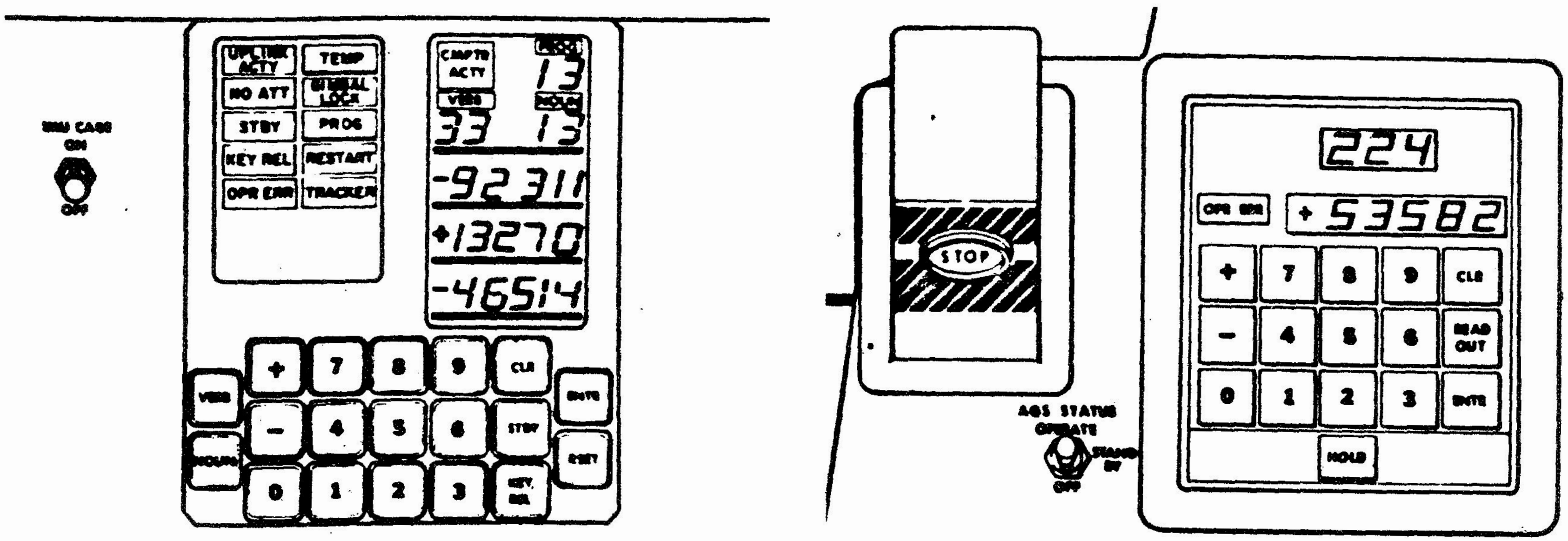


Figure 2.- LM Integrated Block Diagram of PNGCS and AGS.



a. Command Pilot b. Pilot

Figure 3.- LM Flight Instrument Displays



a. DSKY

b. DEDA

Figure 4.- LM Primary and Abort Guidance Computer Input/Output Units

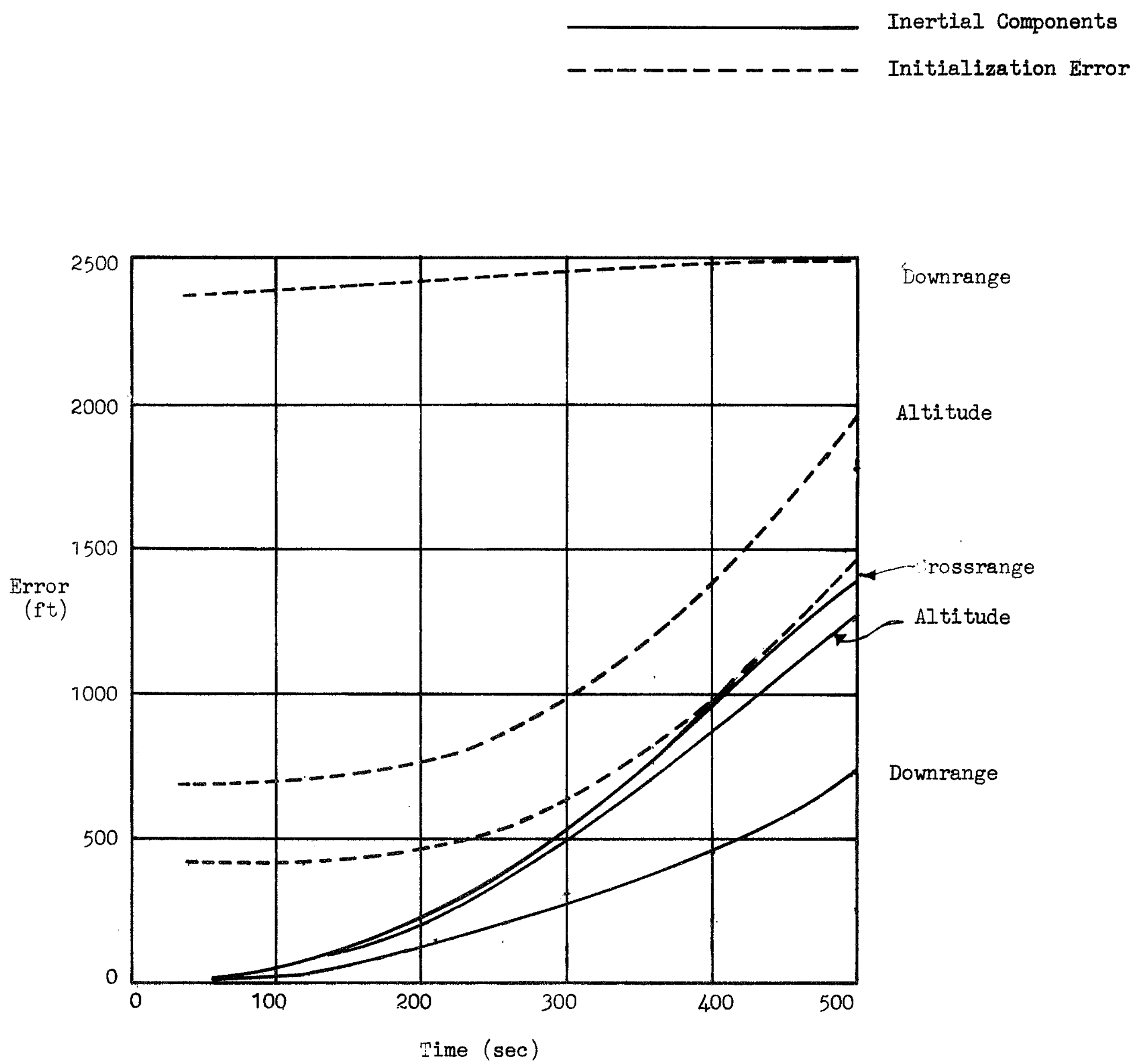


Figure 5a -1 sigma navigation position error (PNGCS)

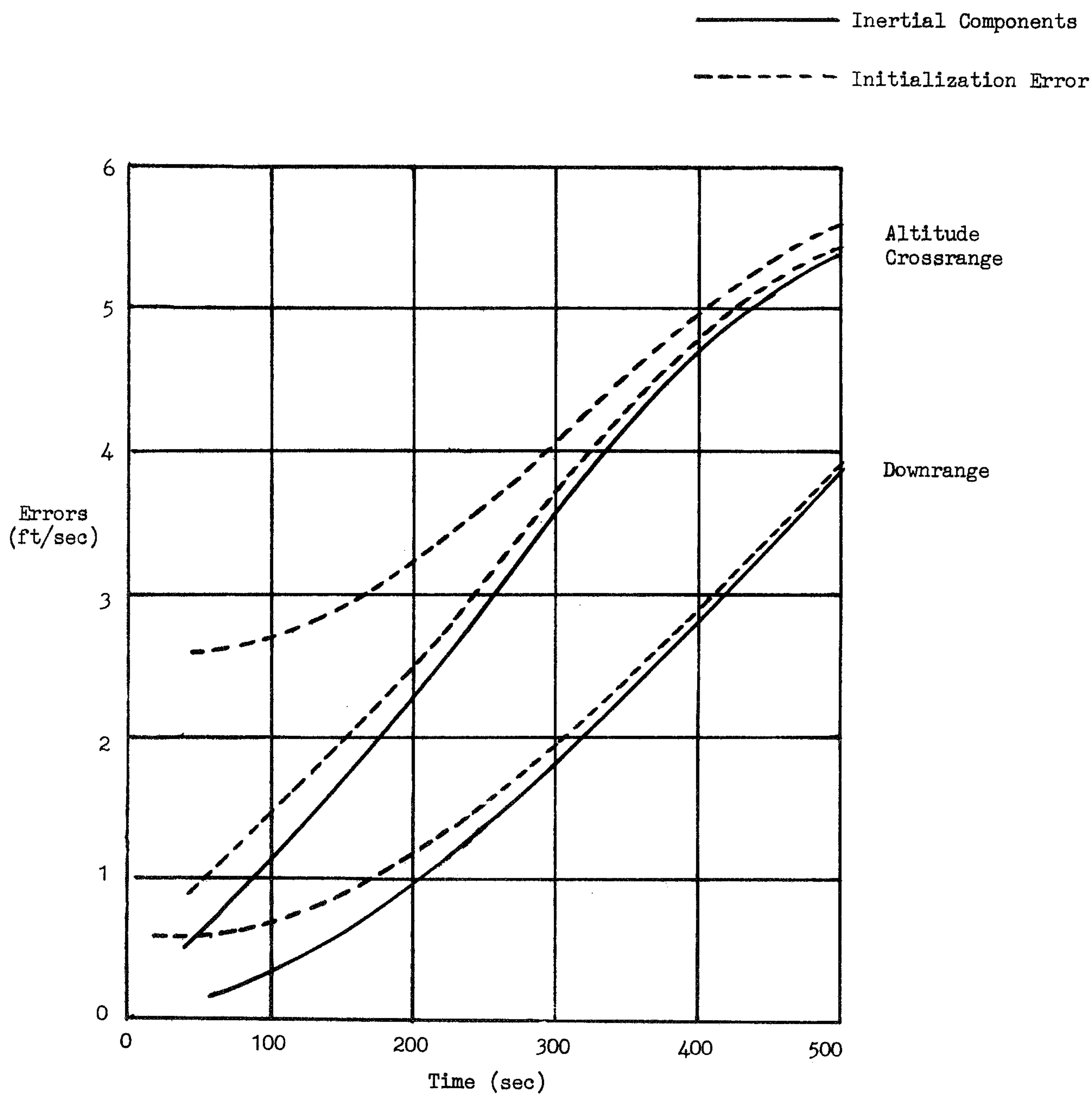


Figure 5b - 1 sigma navigation velocity errors (PNGCS)

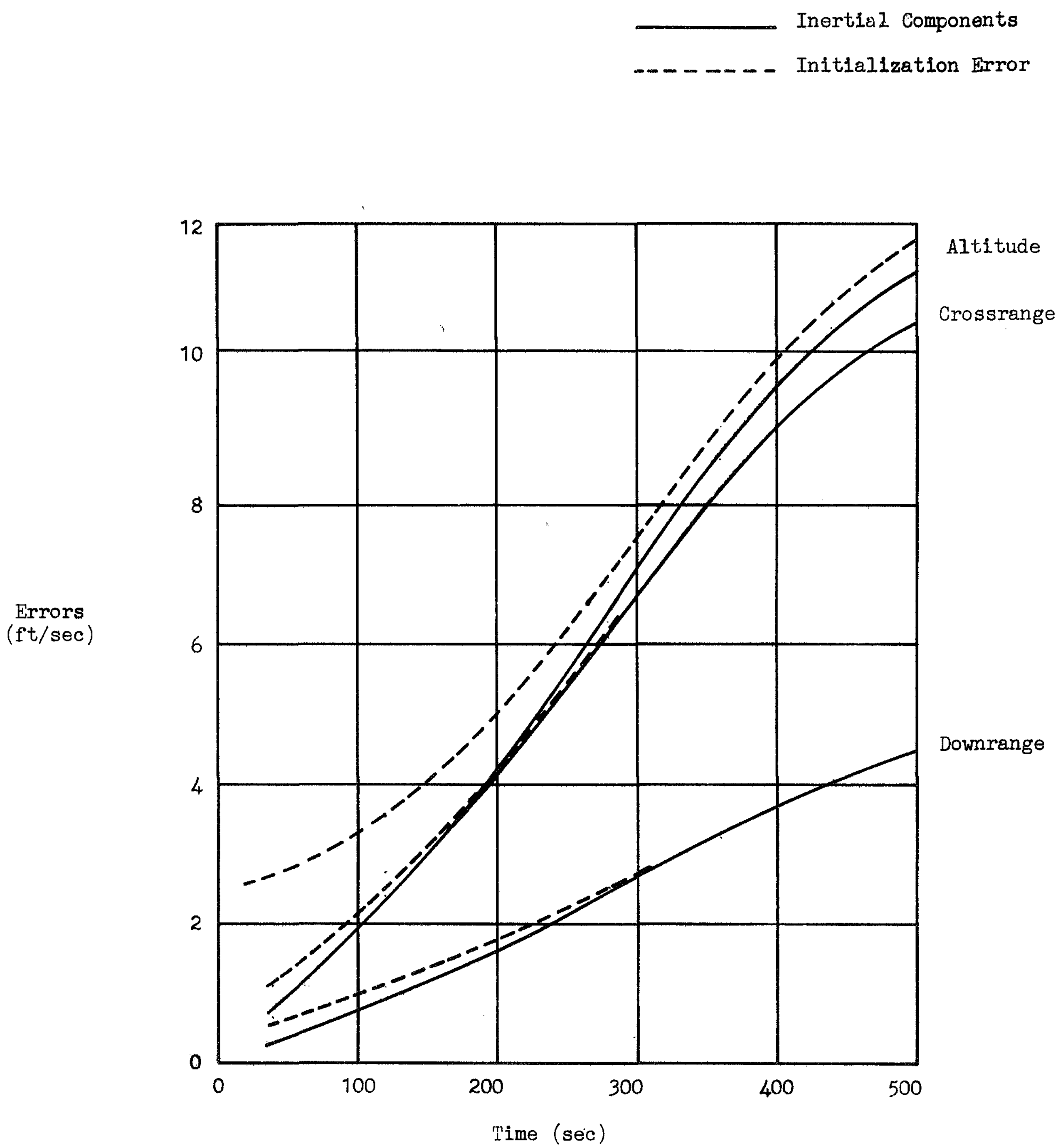


Figure 5c - 1 sigma navigation velocity errors (AGS)

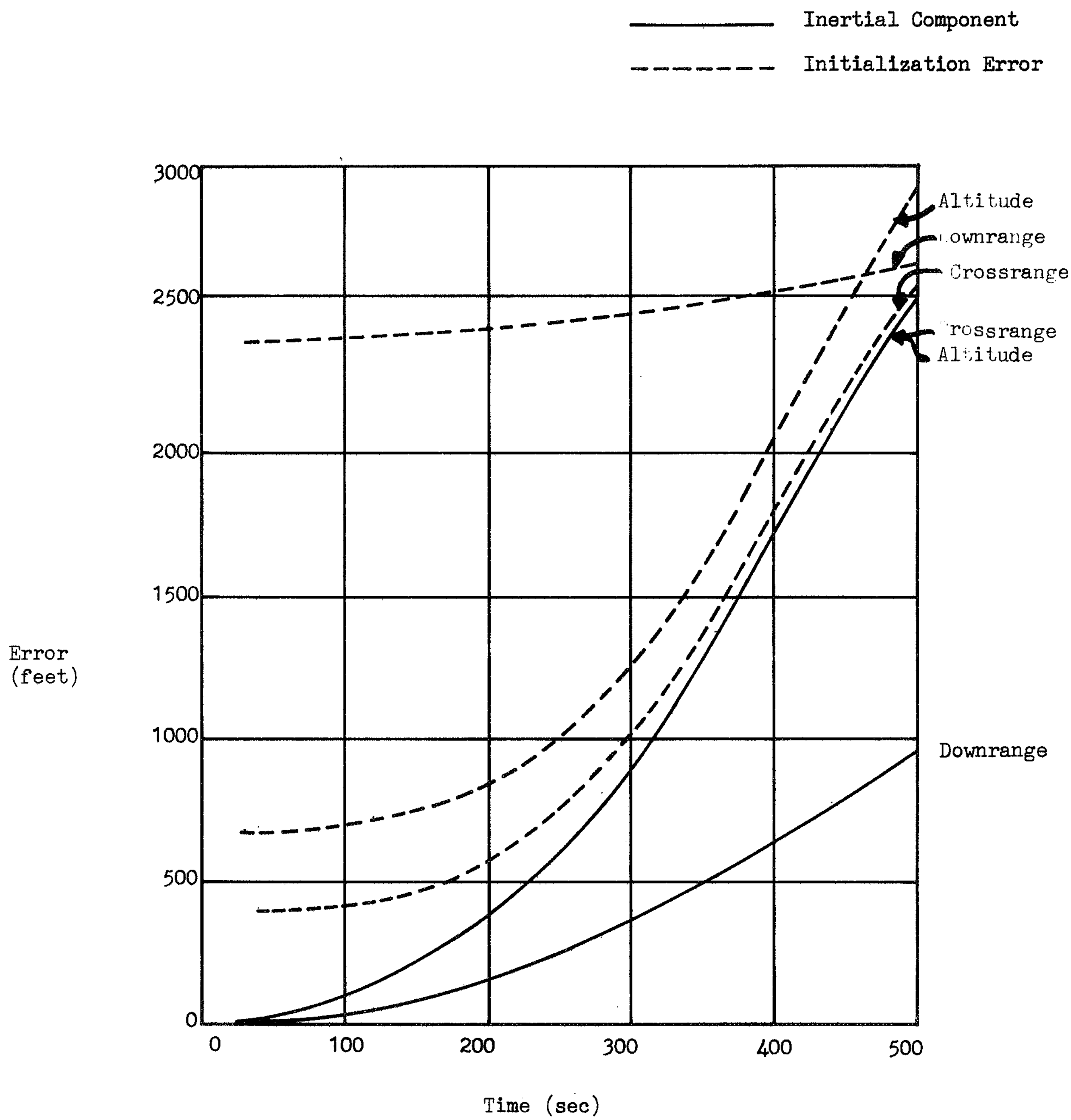


Figure 5d - 1 sigma navigation position errors (AGS)

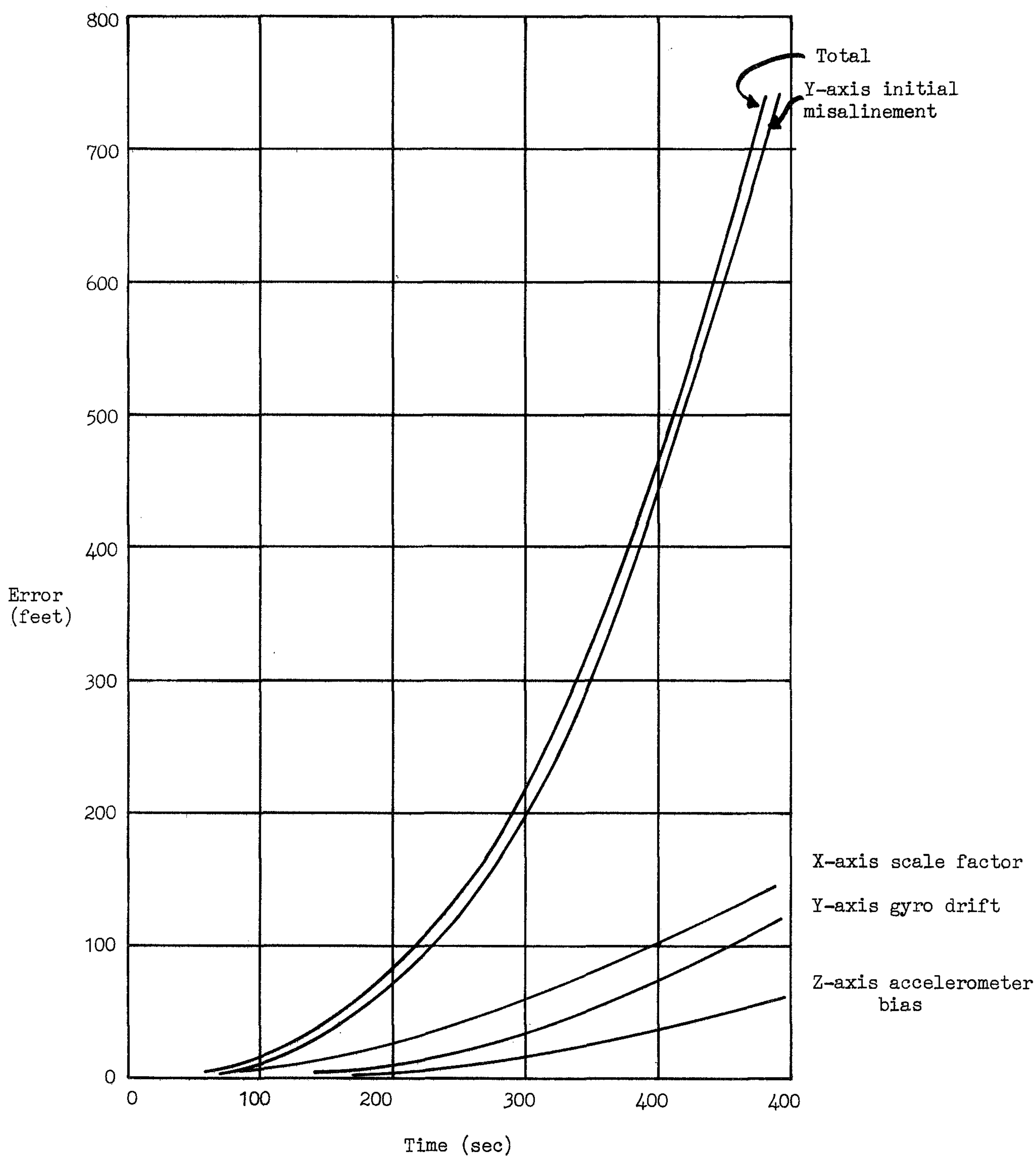


Figure 6a - 1 sigma downrange error (PNGCS)

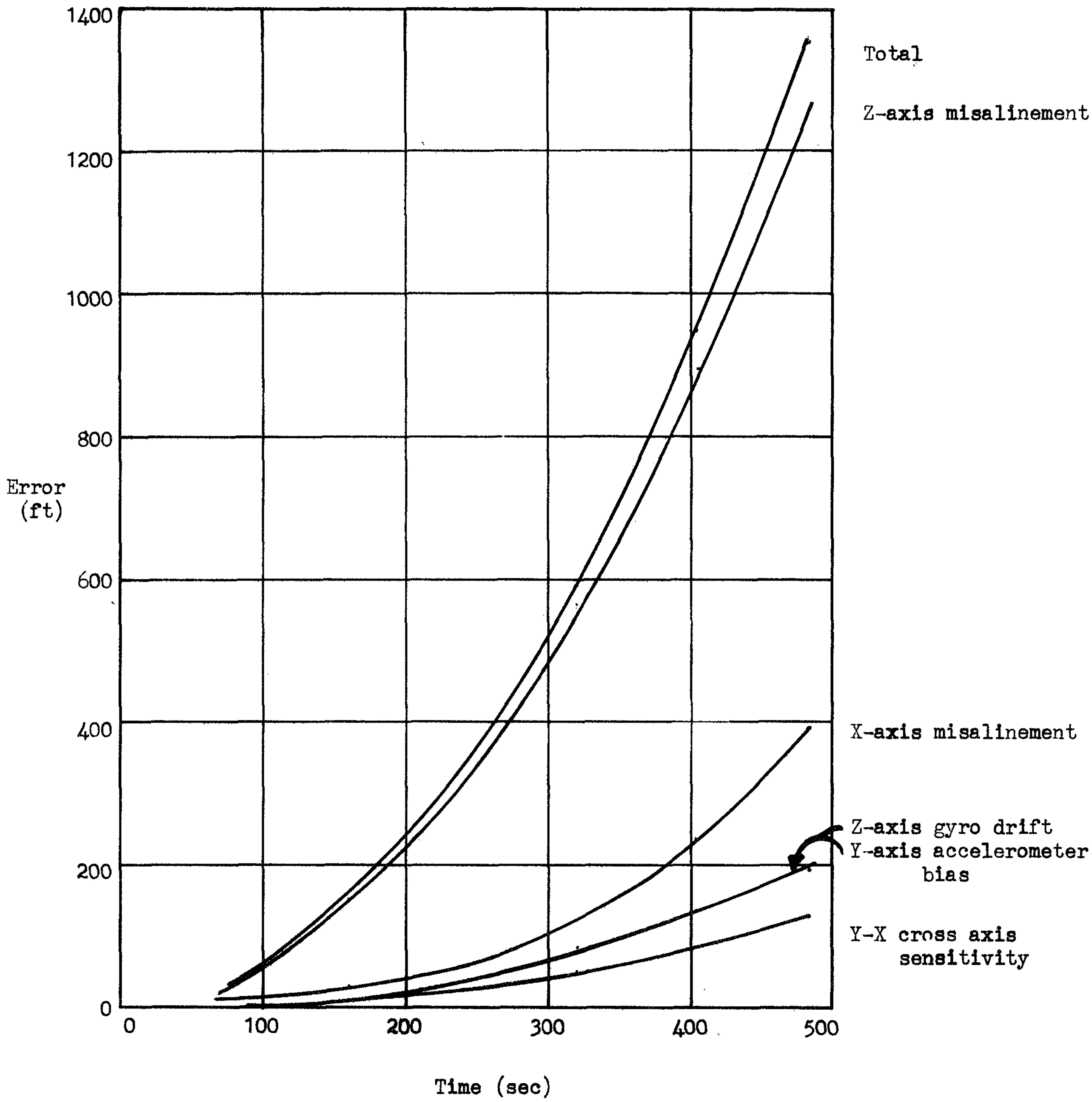


Figure 6b - 1 sigma crossrange error (PNGCS)

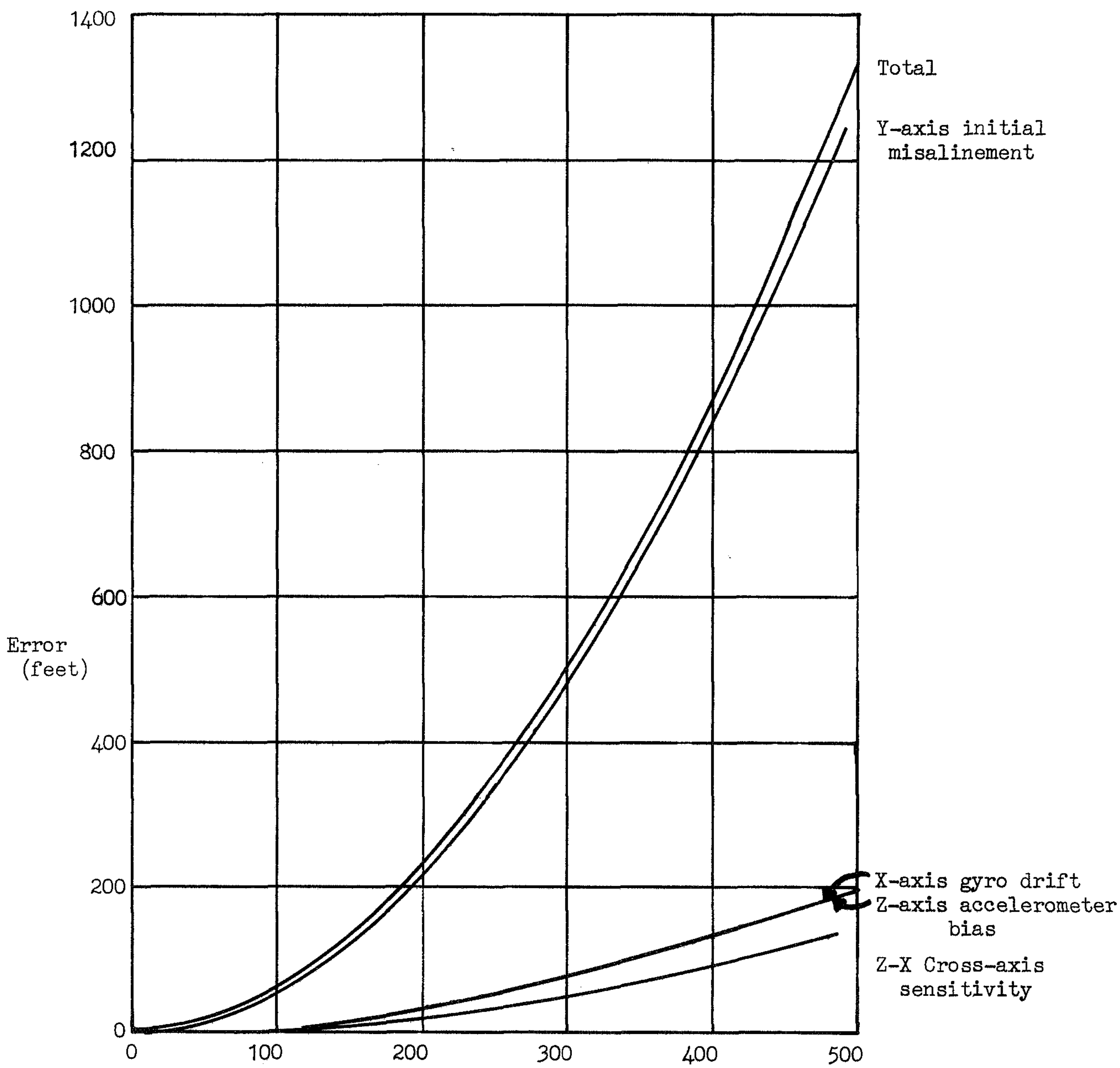


Figure 6c - 1 sigma altitude error (PNGCS)

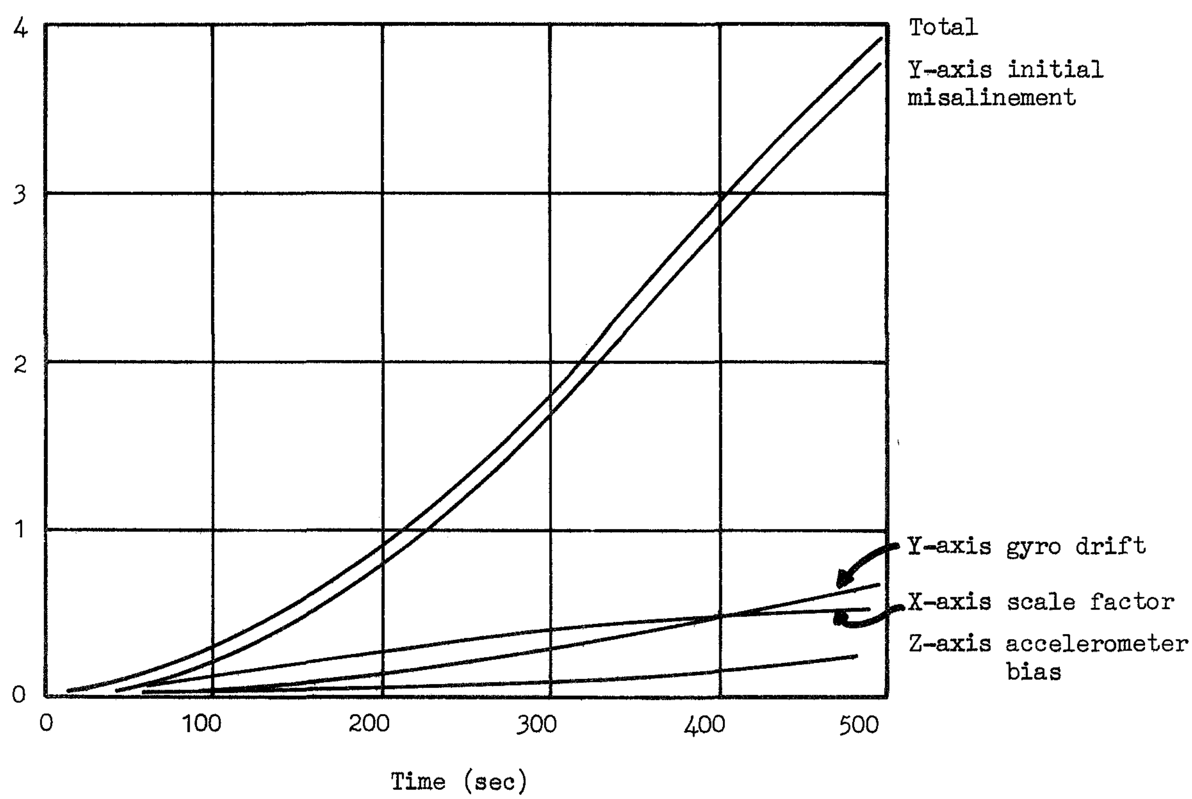


Figure 6d - 1 sigma downrange velocity error (PNGCS)

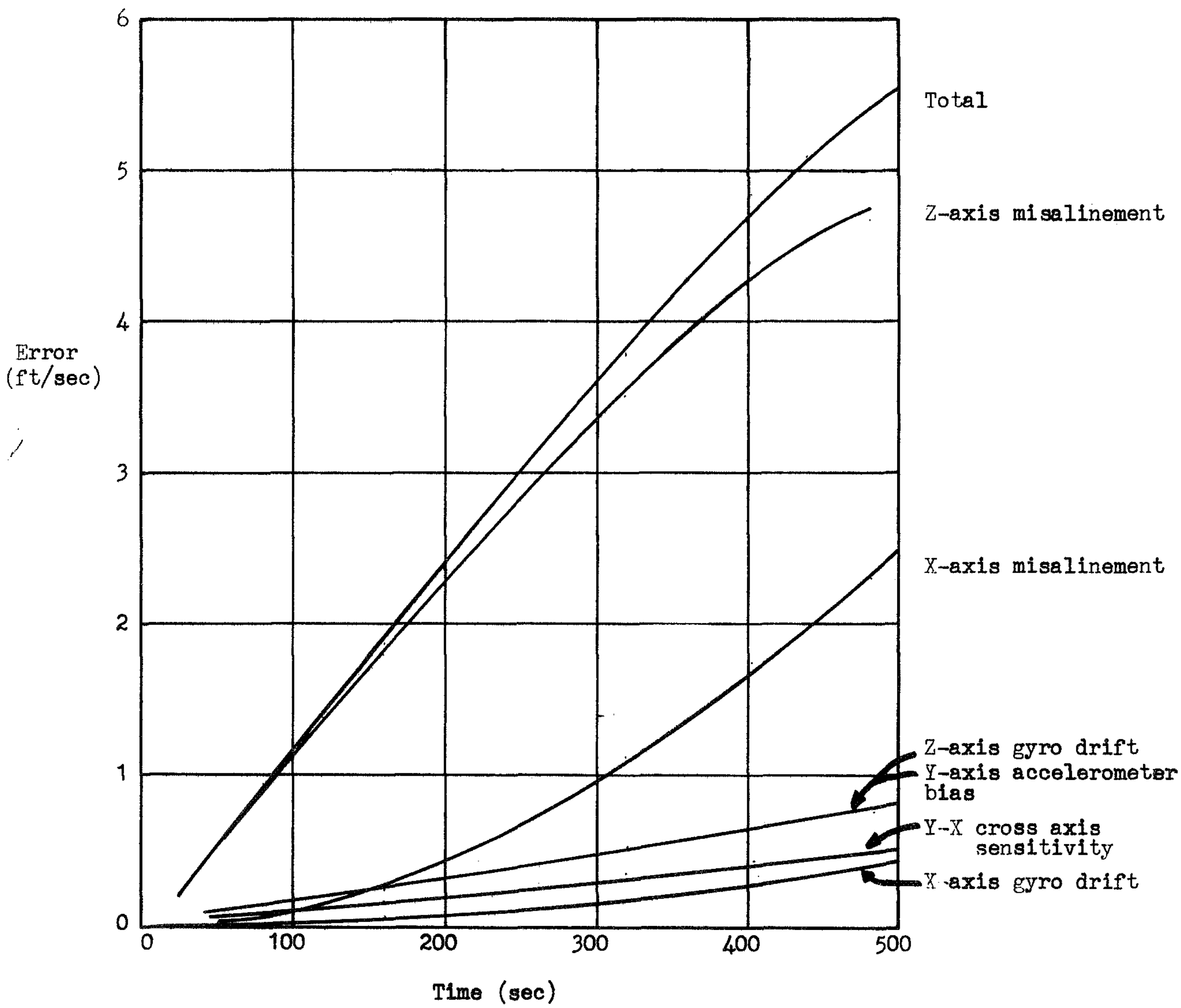


Figure 6e - 1 sigma crossrange velocity error (PNGCS)

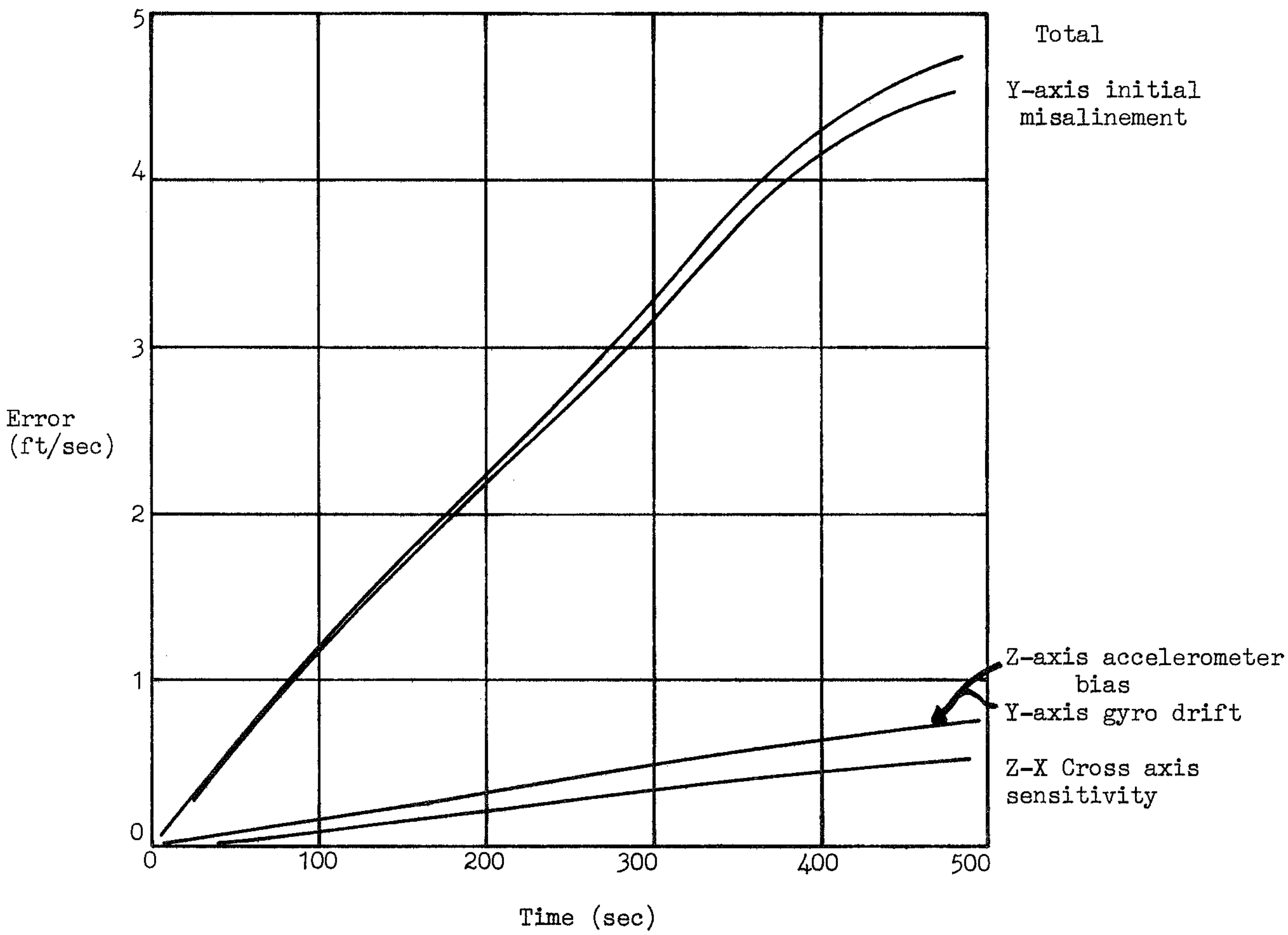


Figure 6f - 1 sigma altitude rate error (PNGCS)

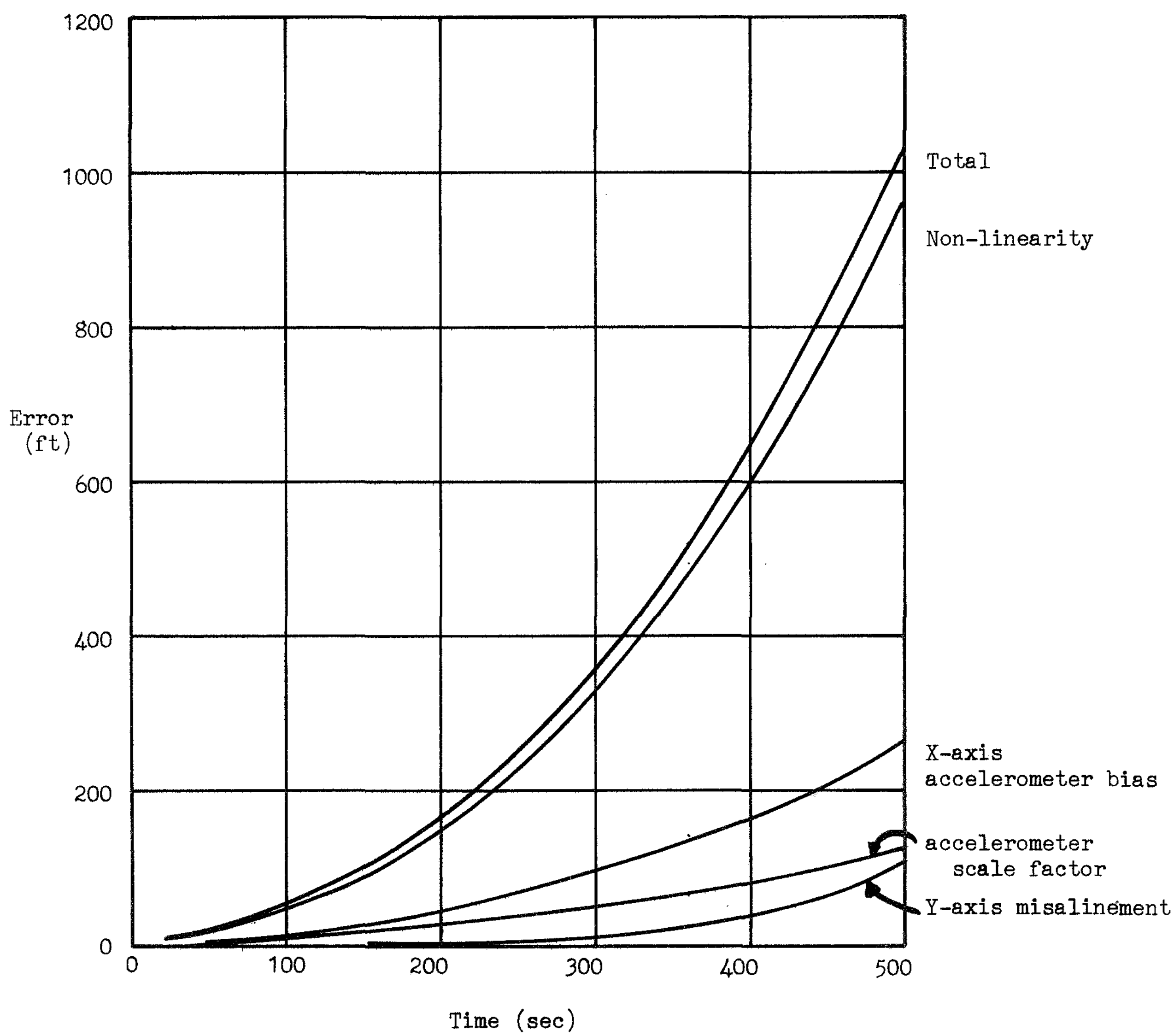


Figure 7a - 1 sigma downrange error (AGS)

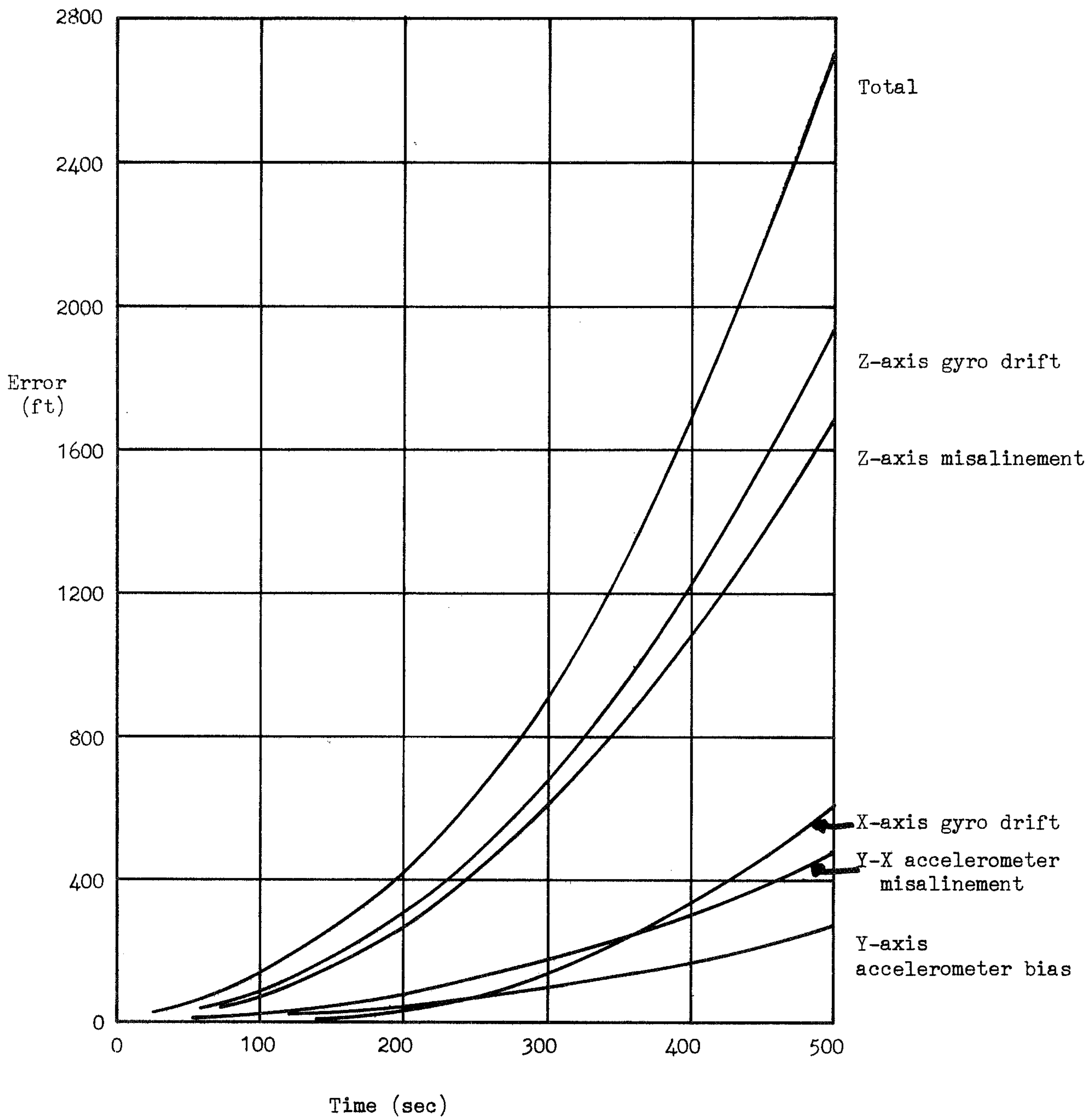


Figure 7b - .1 sigma crossrange error (AGS)

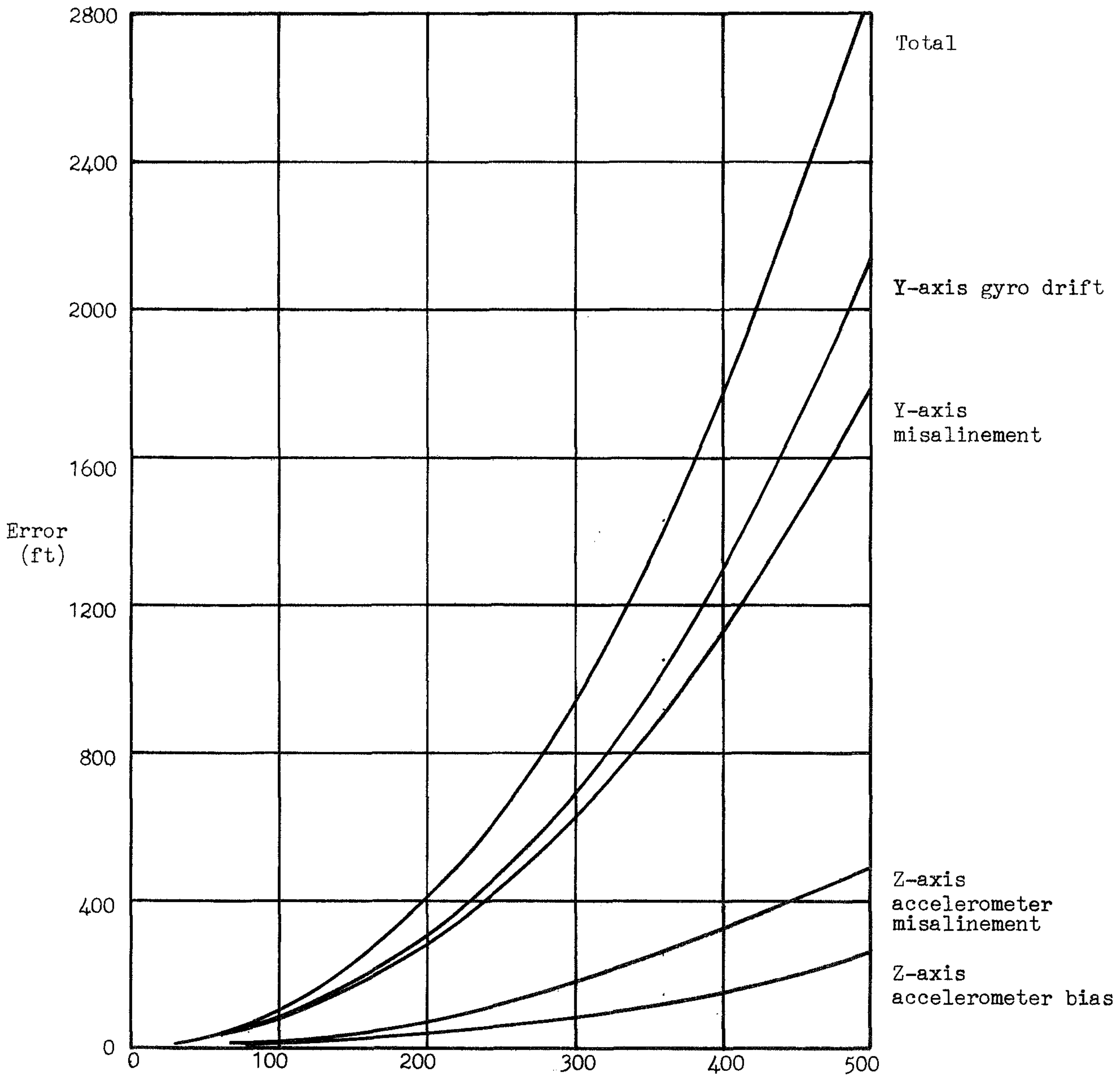


Figure 7c - 1 sigma altitude error (AGS)

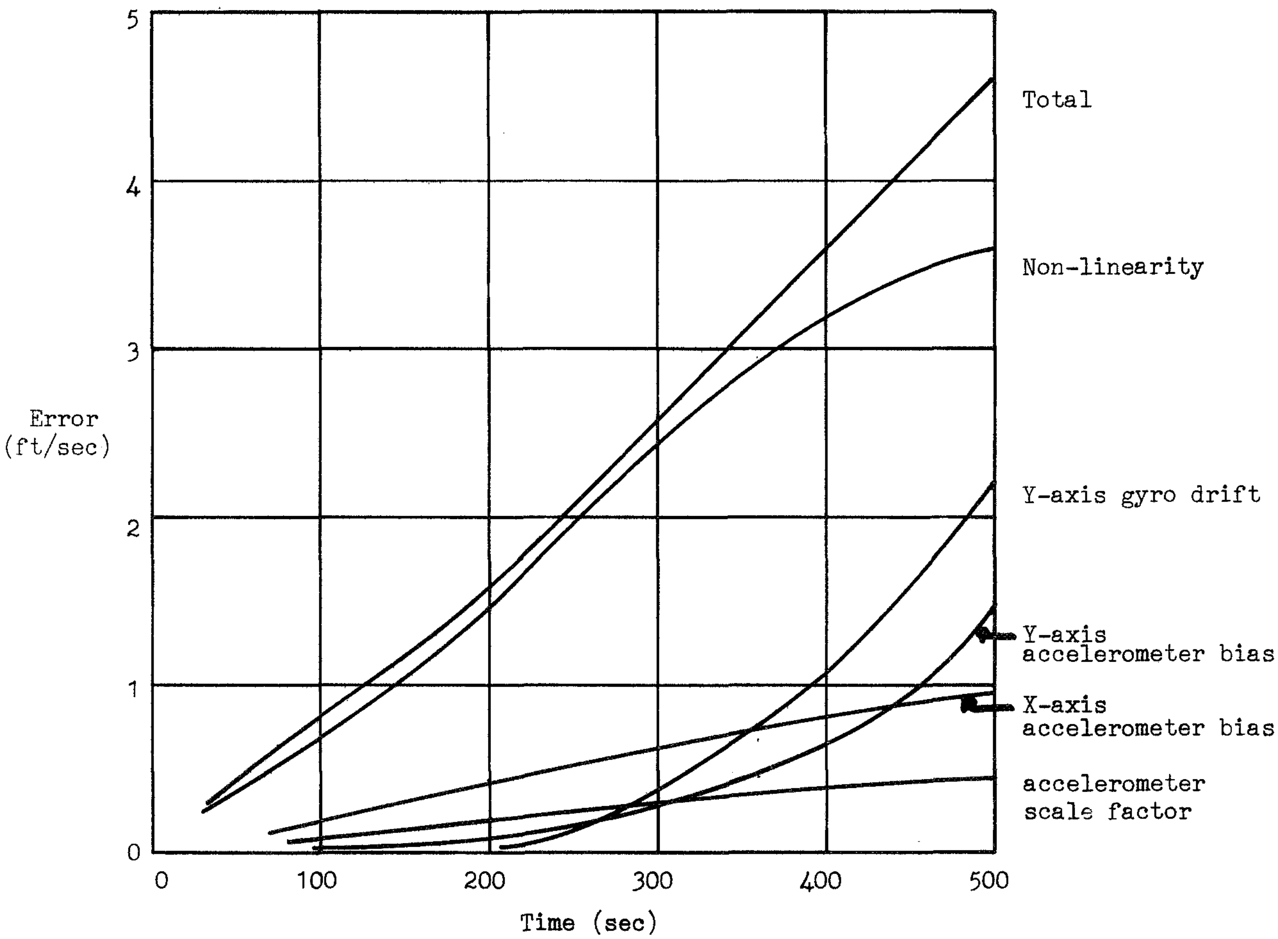


Figure 7d - 1 sigma downrange velocity error (AGS)

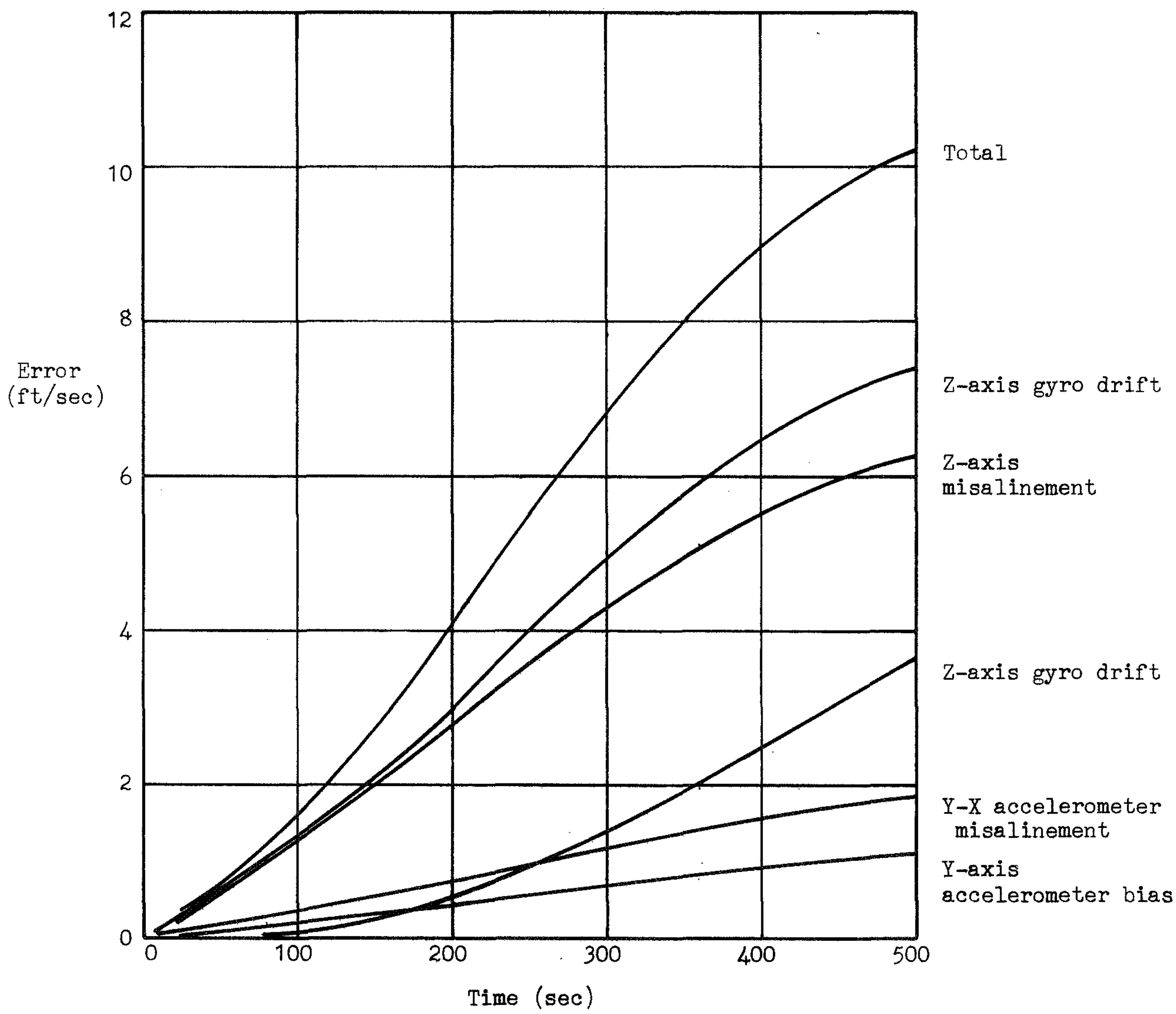


Figure 7e - 1 sigma crossrange velocity error (AGS)

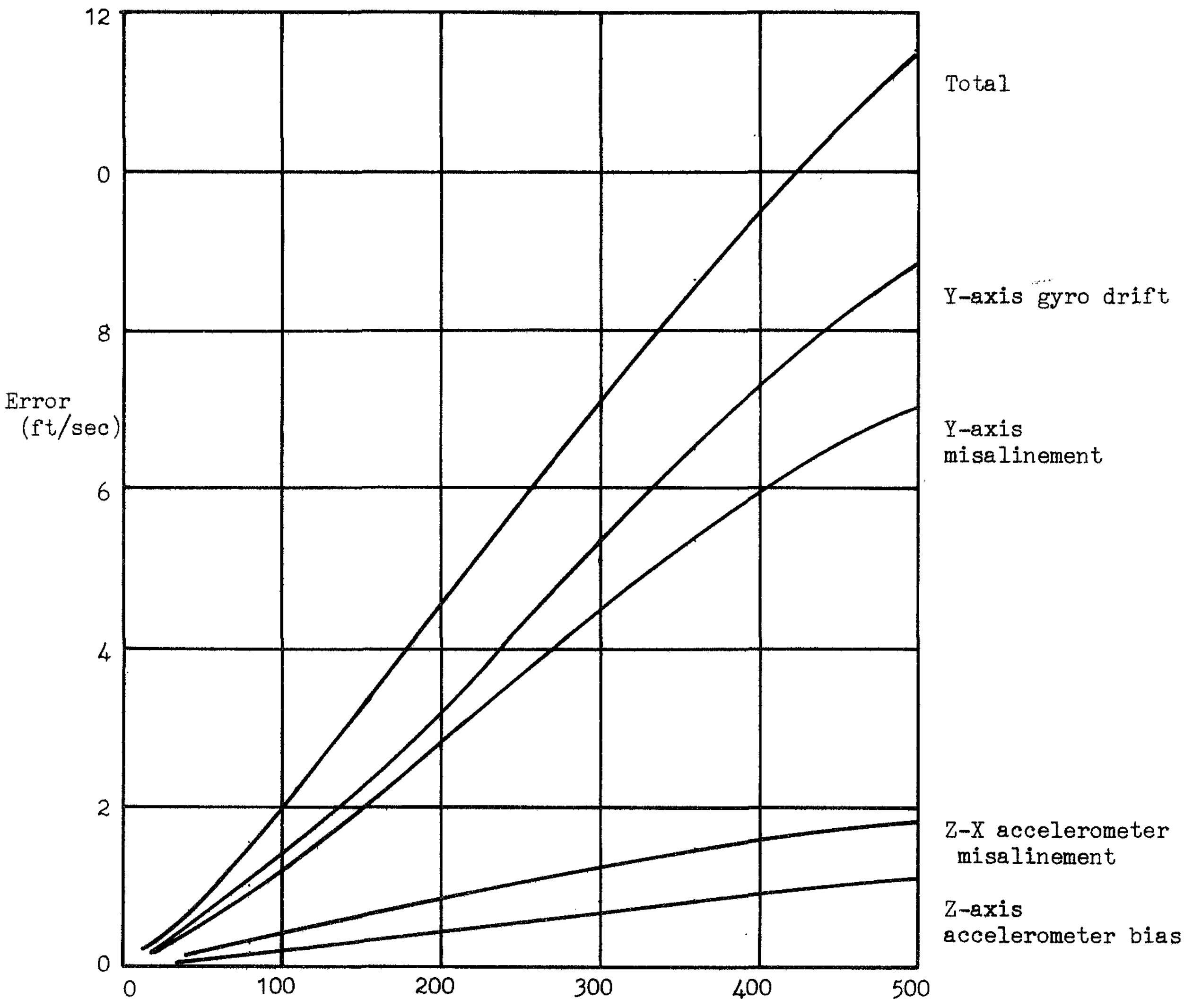
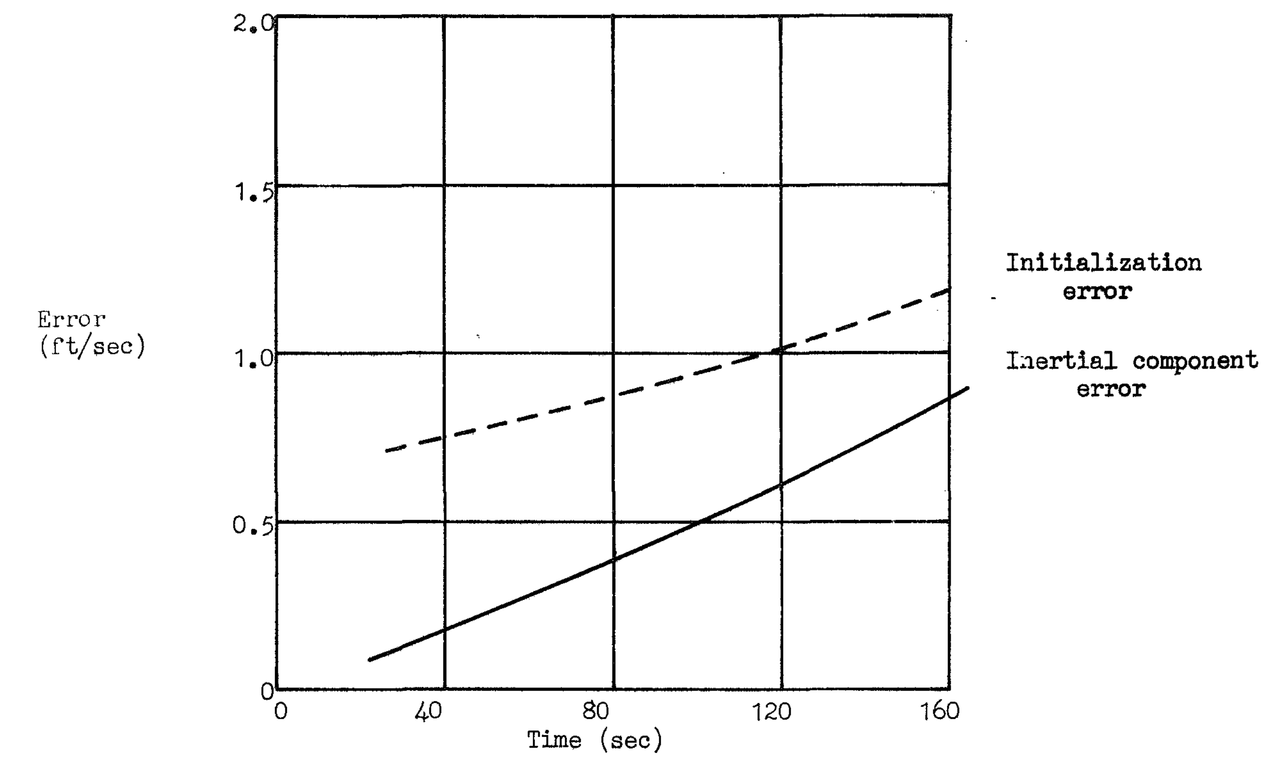
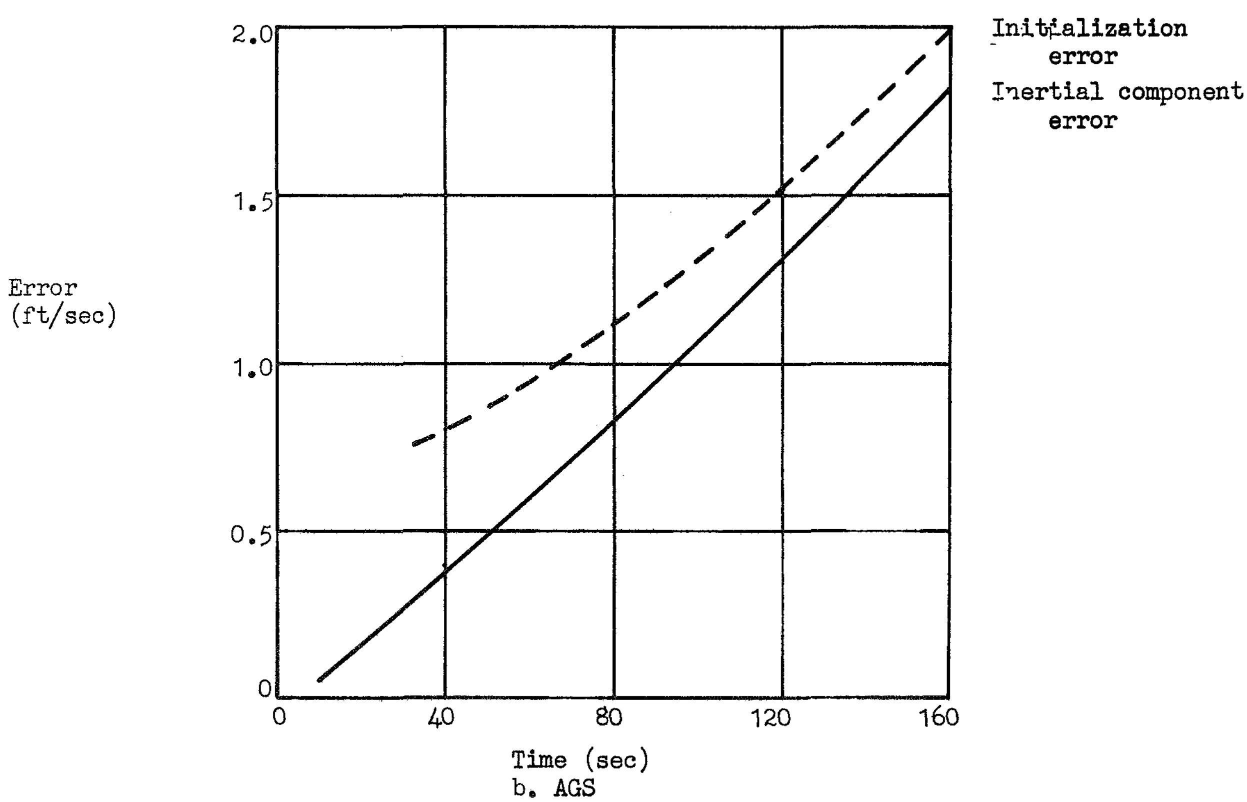


Figure 7f - 1 sigma altitude rate error (AGS)



a. PNGCS



b. AGS

Figure 8 - LM-CSM relative range rate errors in powered descent

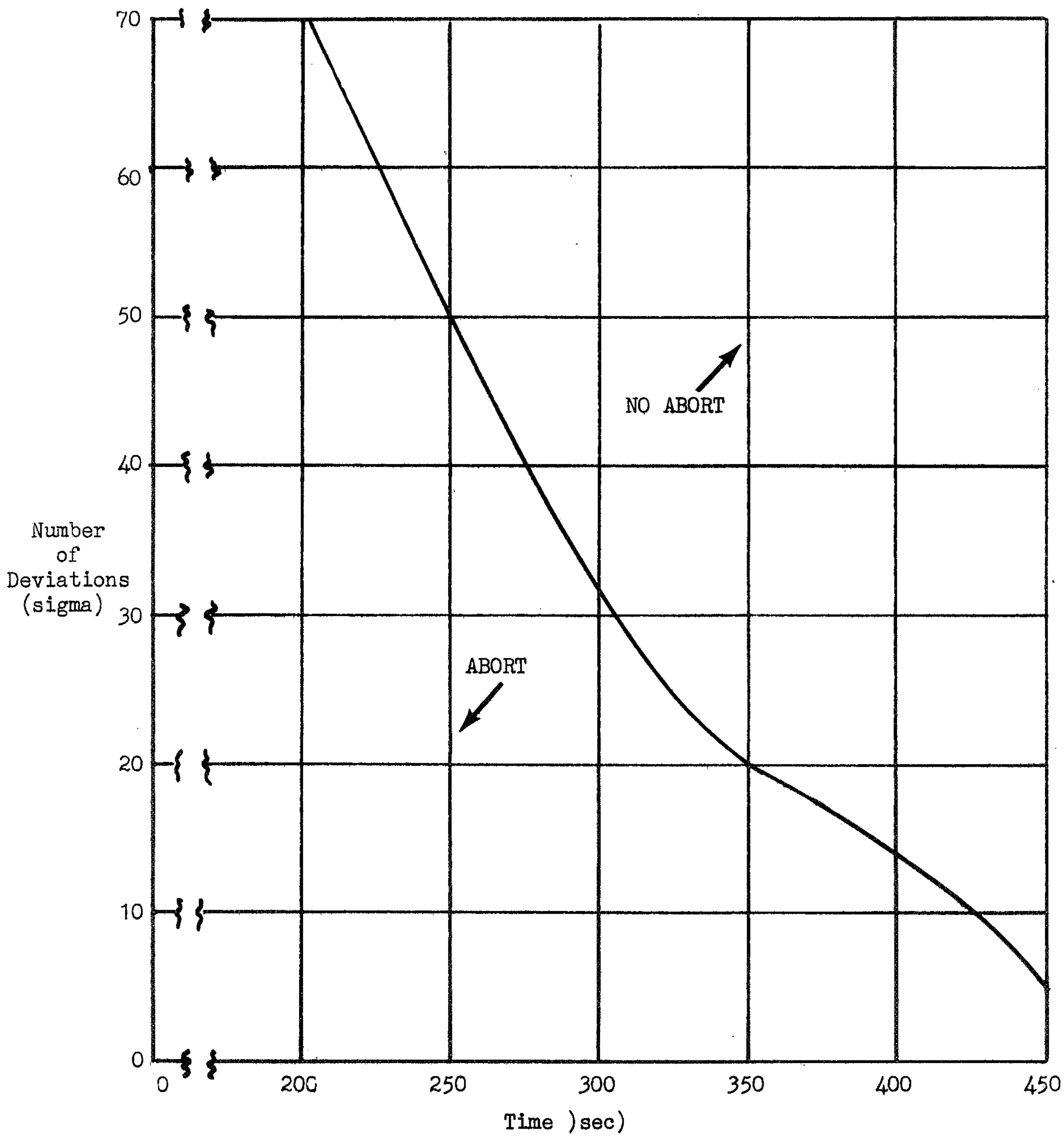


Figure 9 - Number of 1 sigma trajectory deviations in altitude and altitude rate to cause penetration of deadman's curve

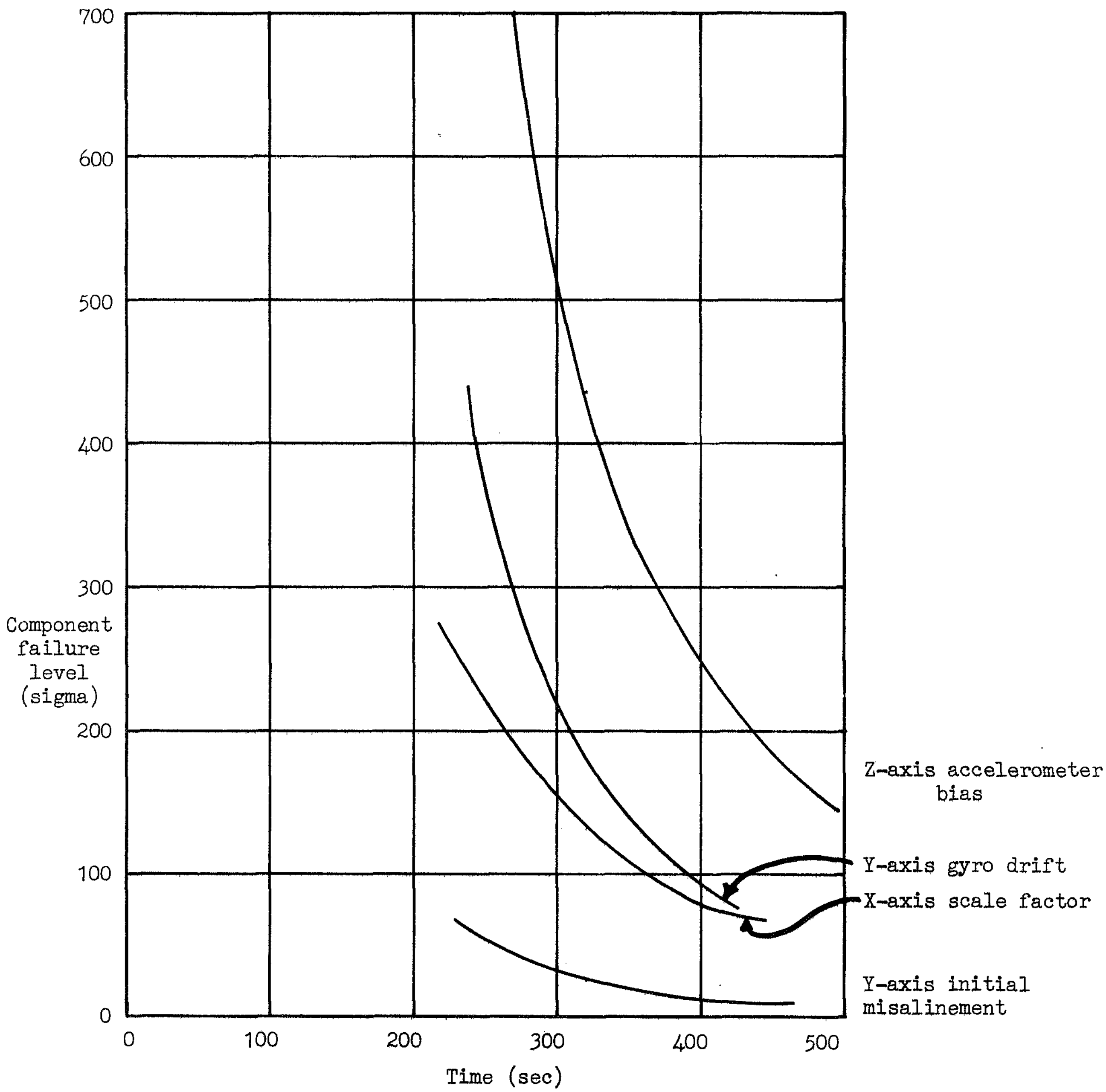


Figure 10 - PNGCS Component failure level required to drive LM into deadman's curve

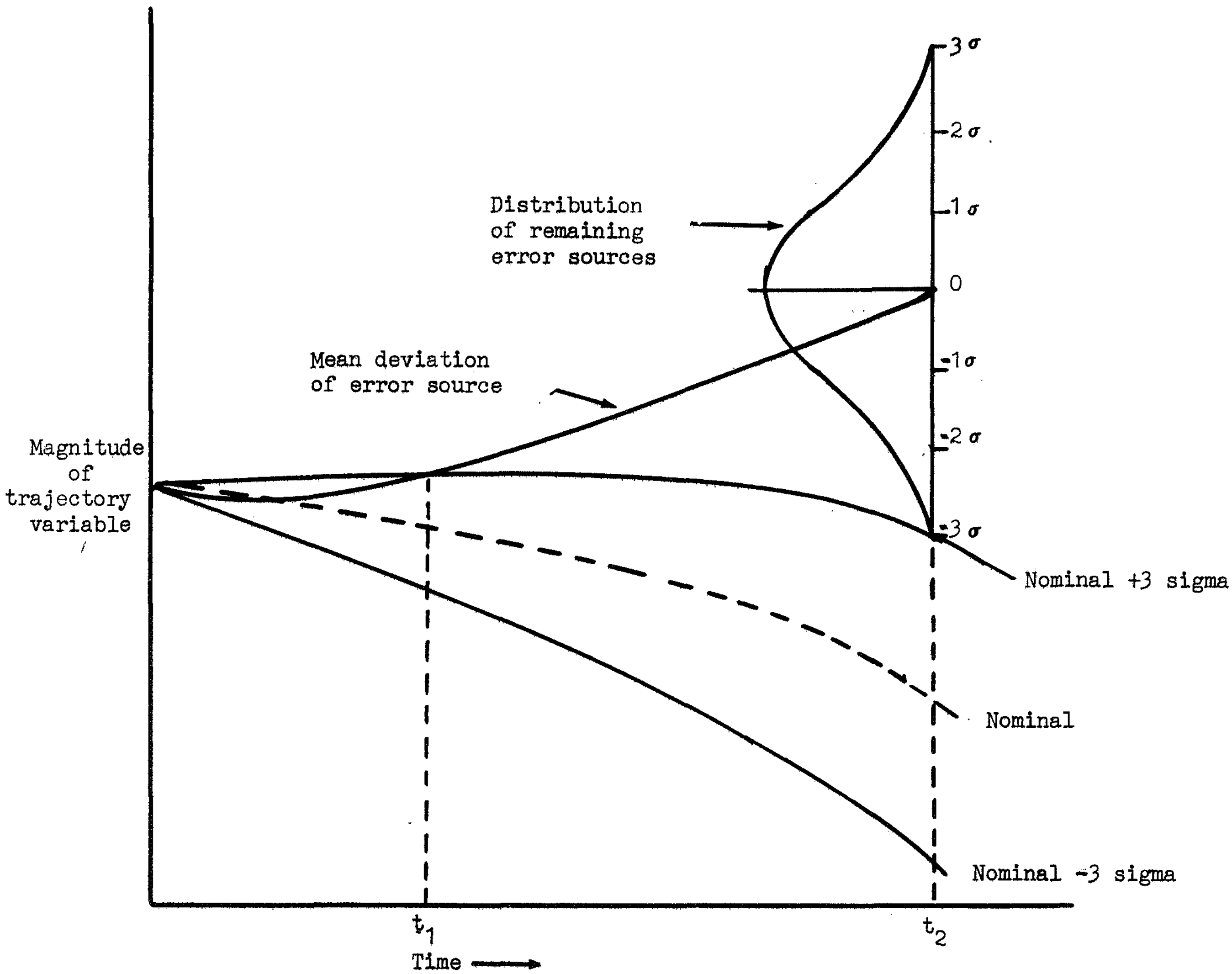


Figure 11 - Detection of Degraded Systems

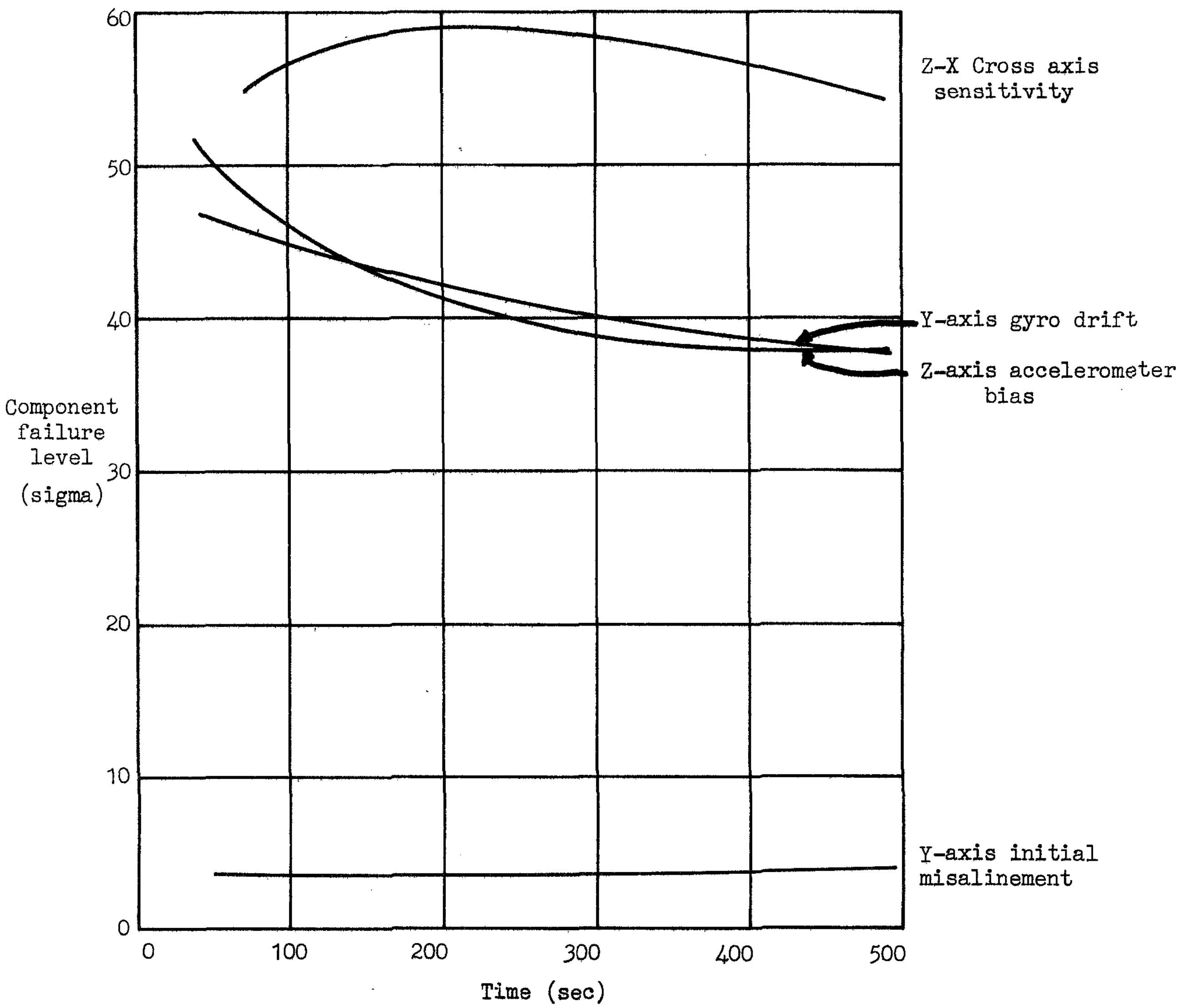


Figure 12 - Component failure level for 99.86% probability of detecting PNGCS failure by monitoring altitude and altitude rate

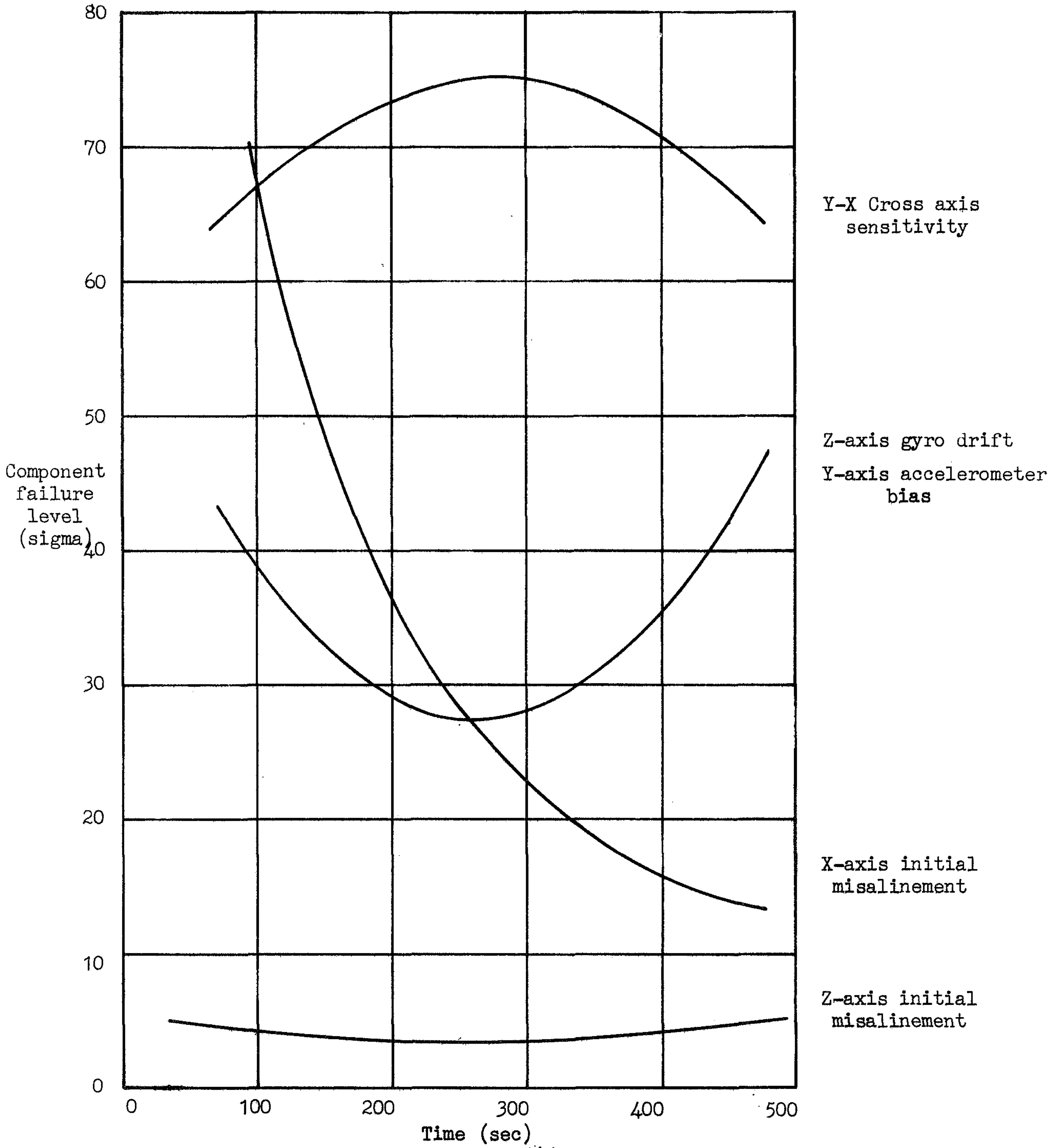


Figure 13 - Component failure level of 99.86% probability of detecting PNGCS failure by monitoring lateral velocity

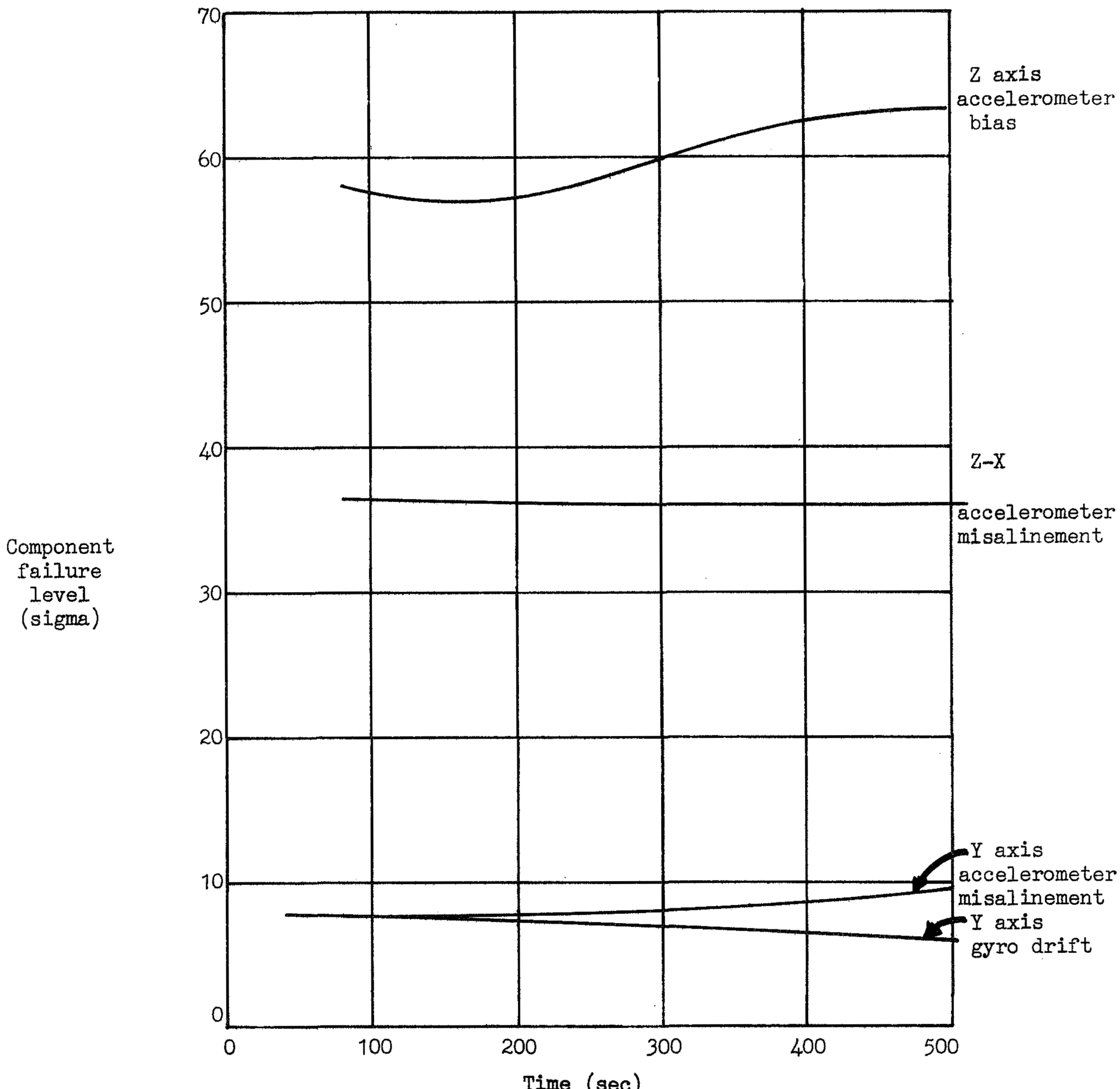


Figure 14 - Component failure level for 99.86% probability of detecting AGS failure by monitoring altitude and altitude rate

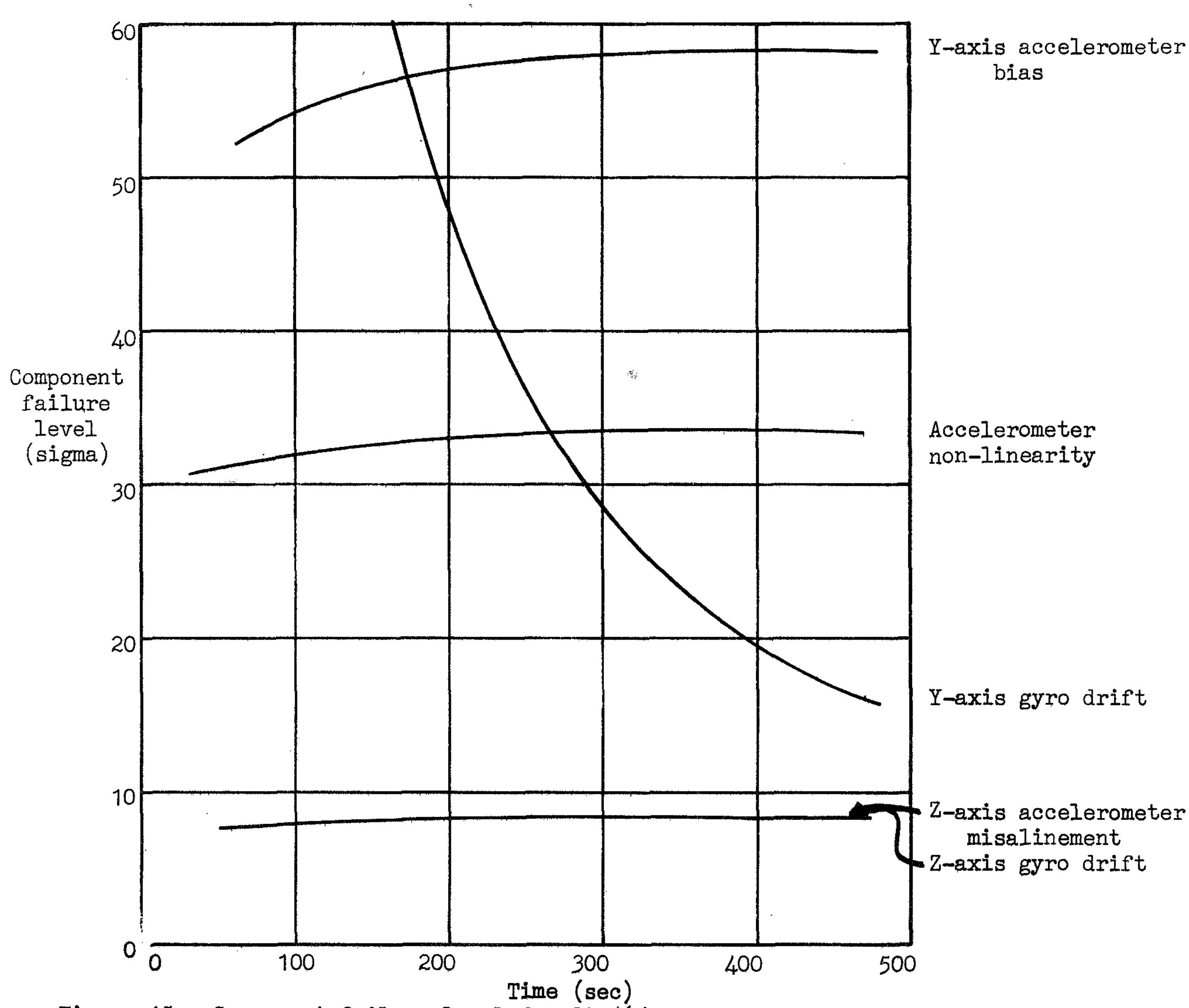


Figure 15 - Component failure level for 99.86% probability of detecting AGS failure by monitoring lateral velocity

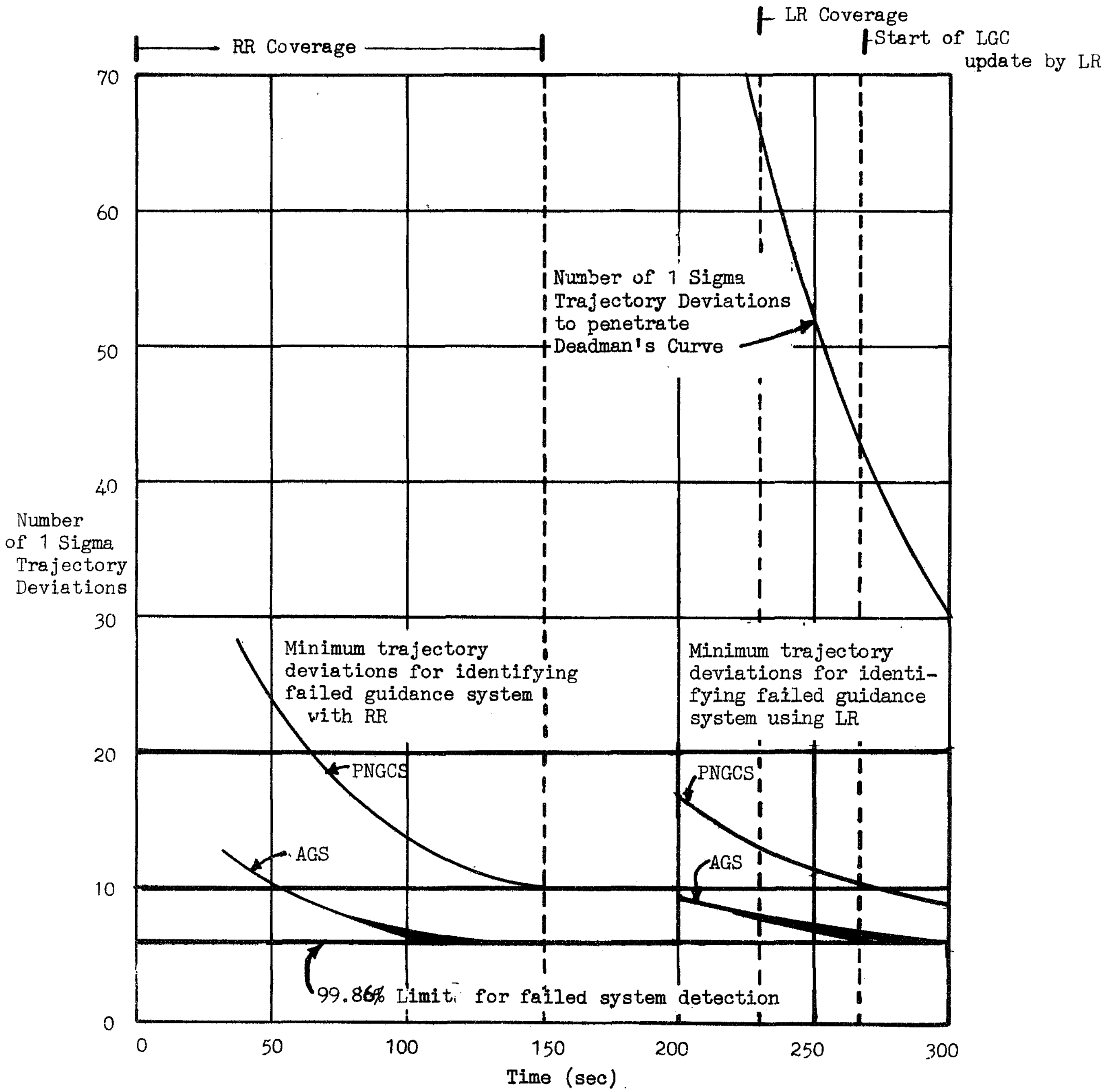


Figure 16 - Number of 1 Sigma Trajectory Deviations Required for Identifying Failed Guidance System Using RR and LR